RIKEN BNL Research Center

Physics Opportunities from the RHIC Isobar Run

This workshop will be held virtually.
January 25–28, 2022

Recent LHC results and connection to the nuclear structure

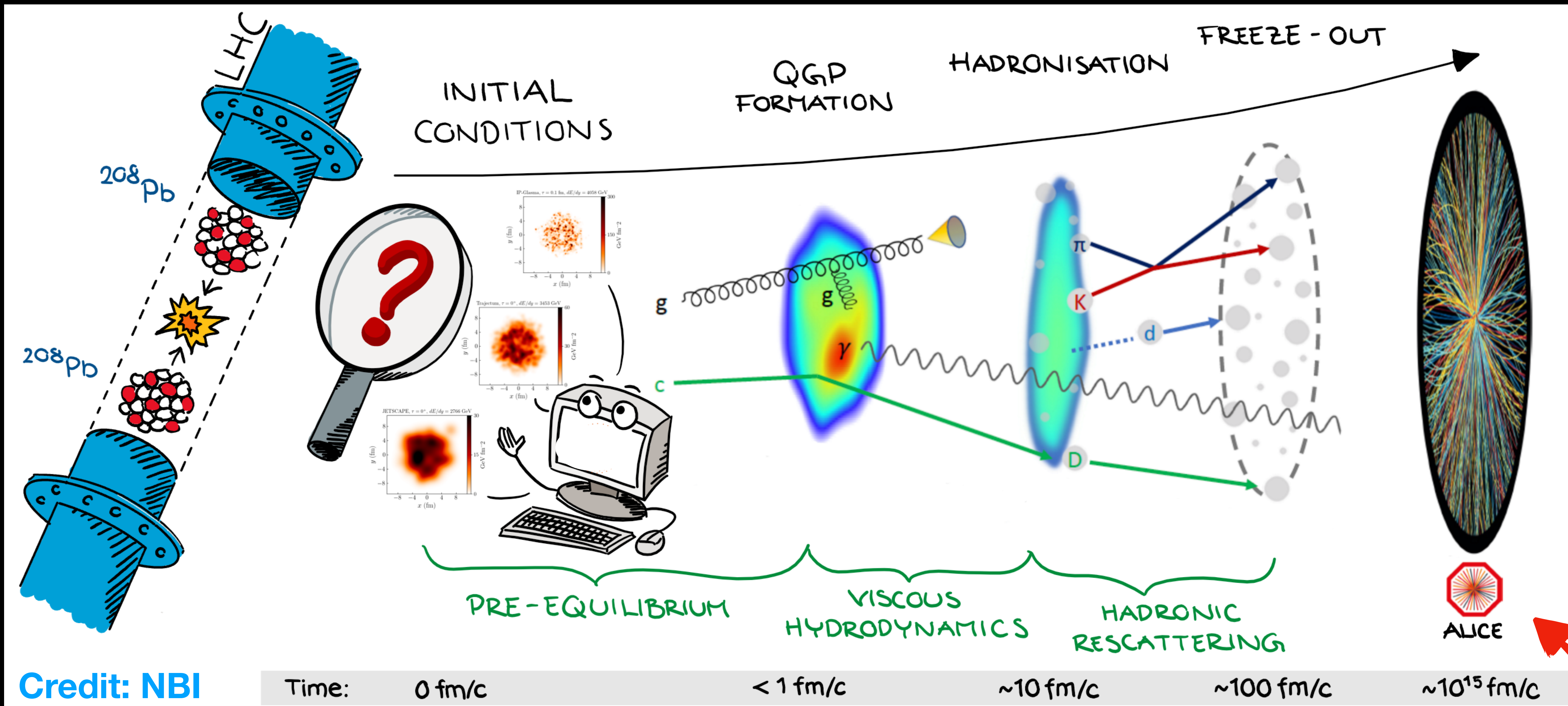
You Zhou (周铀)

Niels Bohr Institute, Copenhagen

UNIVERSITY OF COPENHAGEN

THE VELUX FOUNDATIONS
VILLUM FONDEN VELUX FONDEN

Evolution in the *Little Bang*



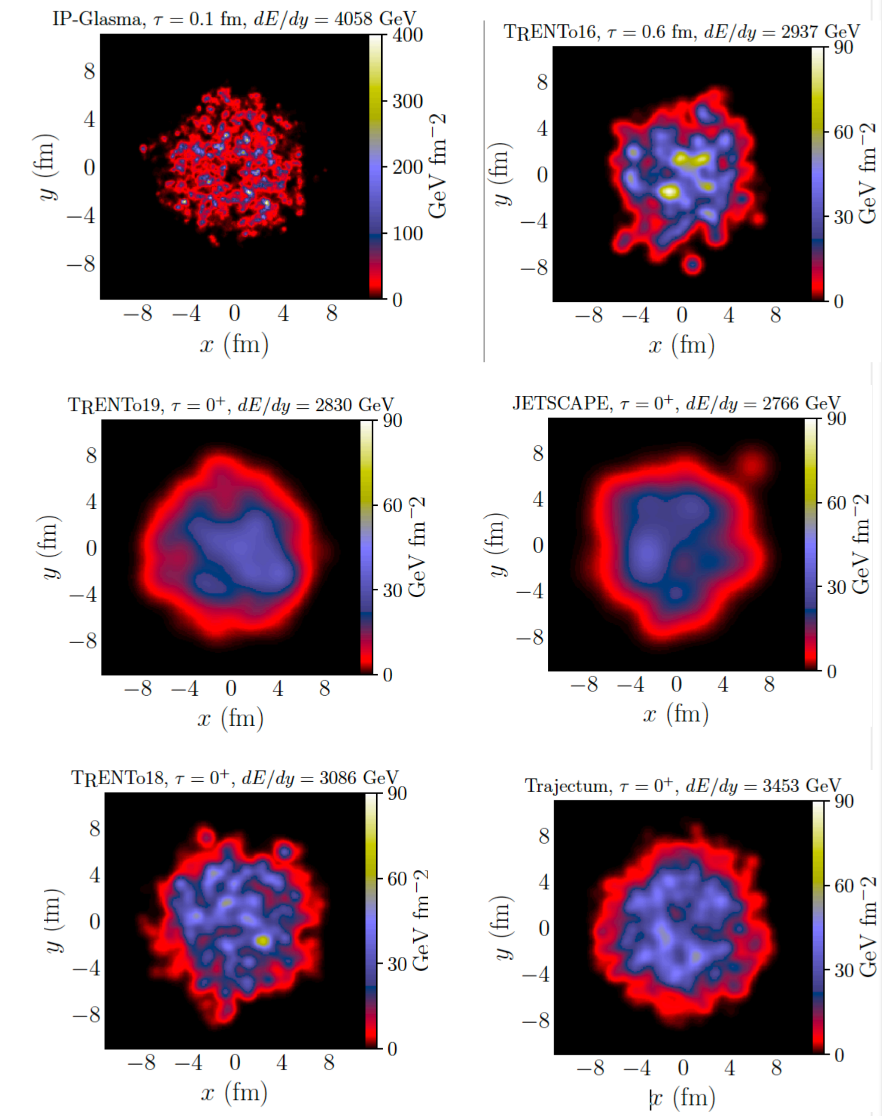
TH

IC → Hydro → Rescattering → Final

Current status of initial state models

Simple example: Pb-Pb collisions (where shape of Pb does not matter)

Credits: G. Giacalone



– **"sharp" models: IP-GLASMA and TRENTo 2016**

[Schenke, Shen, Tribedy 2005.14682]

[Bass, Bernhard, Moreland 1605.03954]

Nucleons have a width of ~0.5fm (trento), 3 sub-nucleons with size ~0.1fm (IP-Glasma). Trento is used for the entropy density at the beginning of hydro.

– **"fat" models: TRENTo 2019 and JETSCAPE**

[Bass, Bernhard, Moreland Nature Phys. 15 (2019)]

[JETSCAPE Collaboration 2011.01430, 2010.03928]

[Parkkila, Onnerstad, Kim 2106.05019]

The Trento parametrization is now used for the energy density at tau=0+. There is no substructure. The nucleon width is now ~1fm. Very smooth profiles.

– **"bumpy" models: TRENTo 2018 and Trajectum**

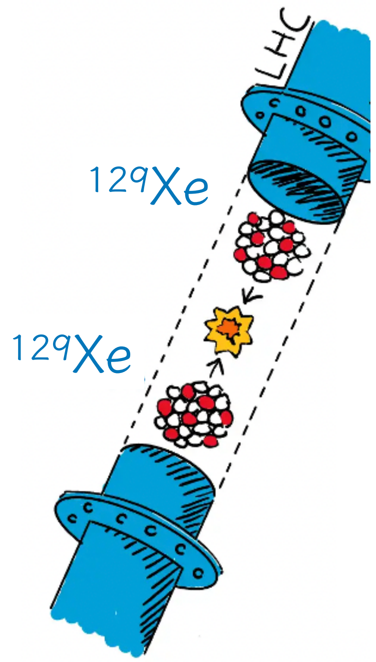
[Bass, Bernhard, Moreland 1808.02106]

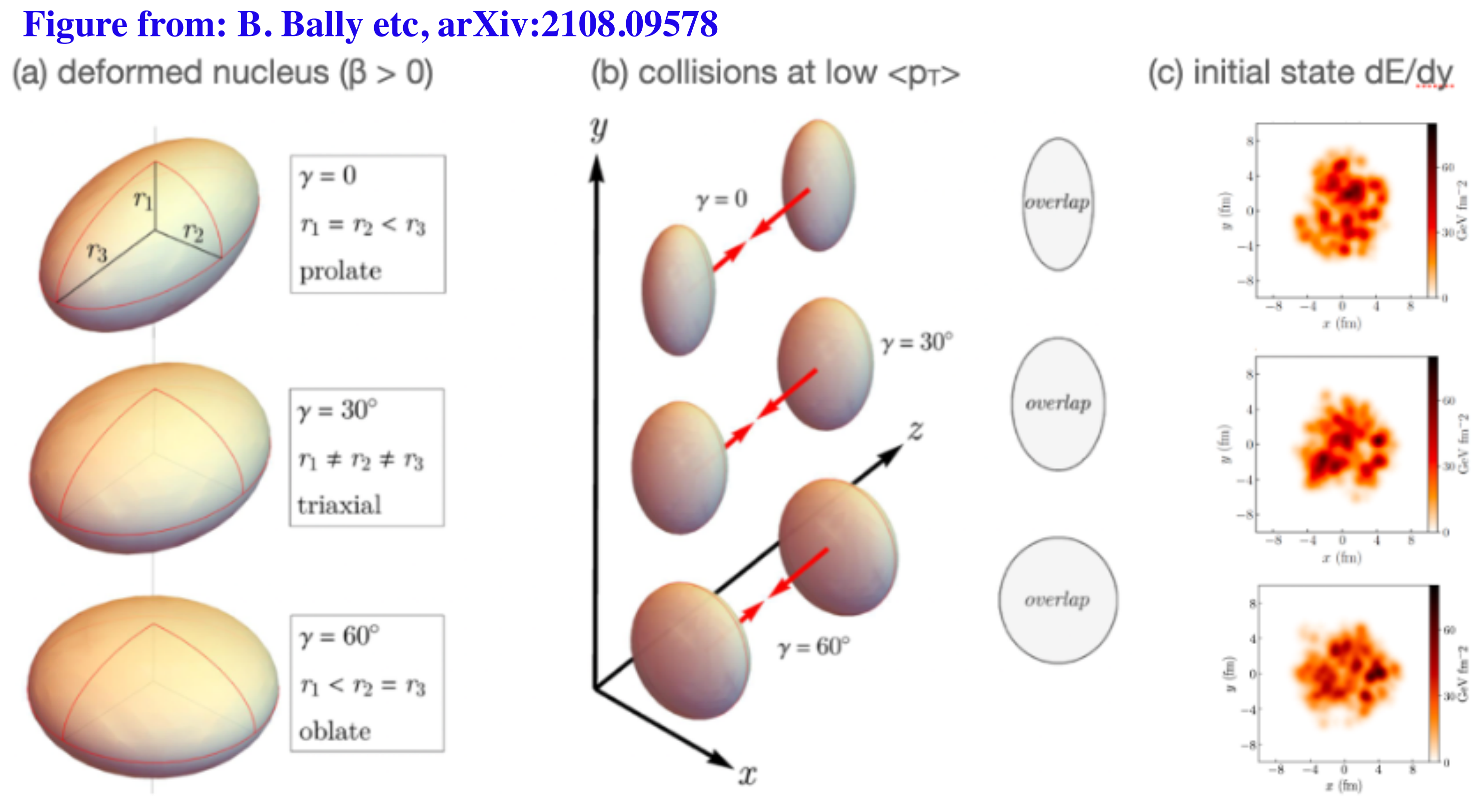
[Nijs, van der Schee, Gürsoy, Snellings 2010.15130, 2010.15134]

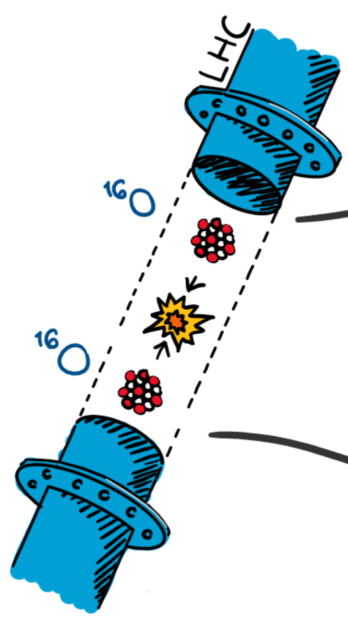
The Trento parametrization is the energy density at tau=0+. Substructure is included: 4-6 constituents with width ~0.4fm. Profiles with some lumpiness.

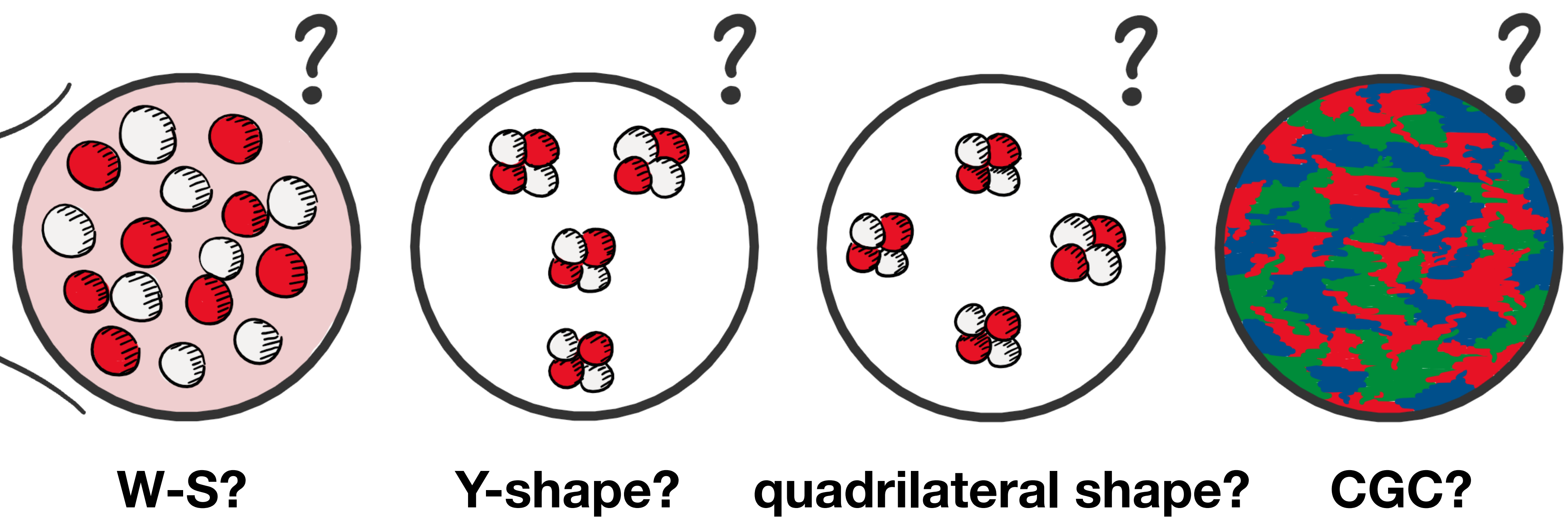
How can we access the initial conditions in EXP ?

Opportunities at the LHC: ^{129}Xe and ^{16}O



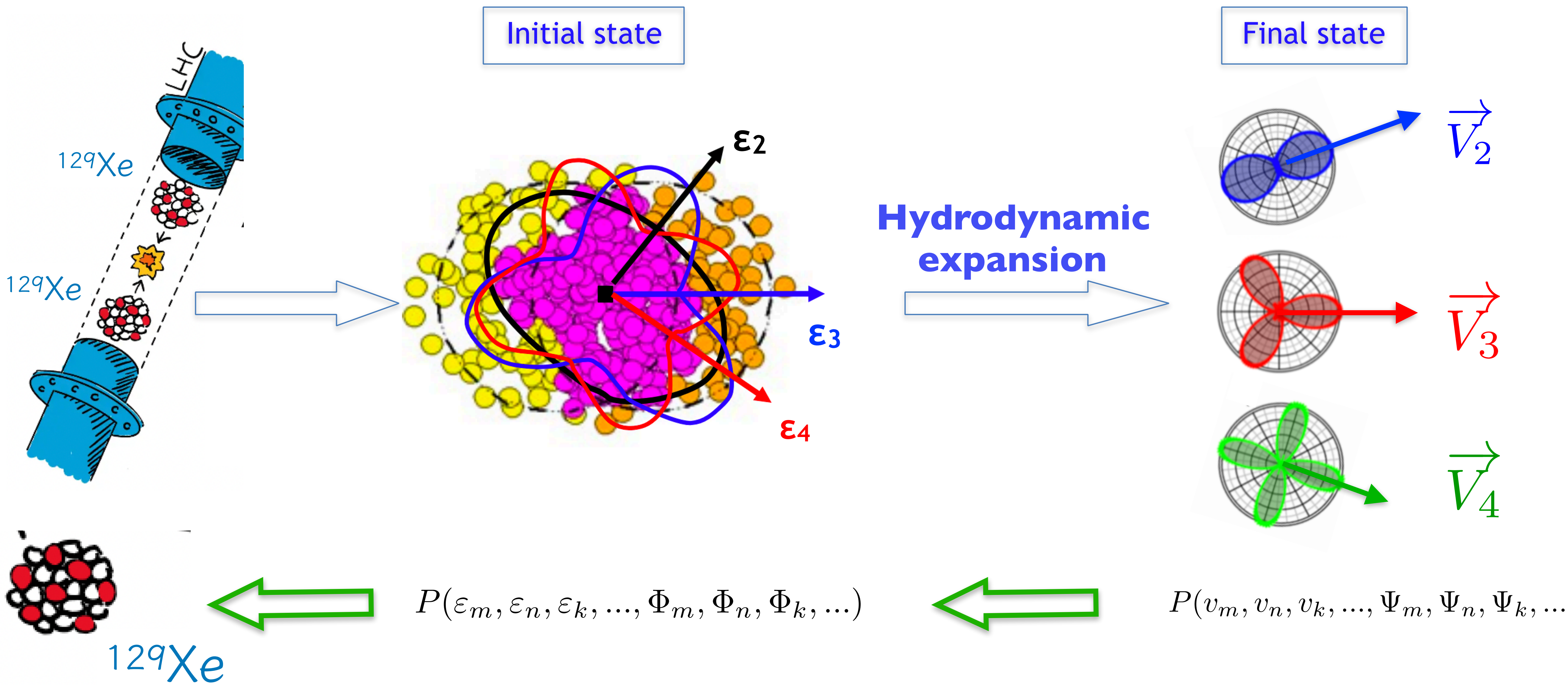






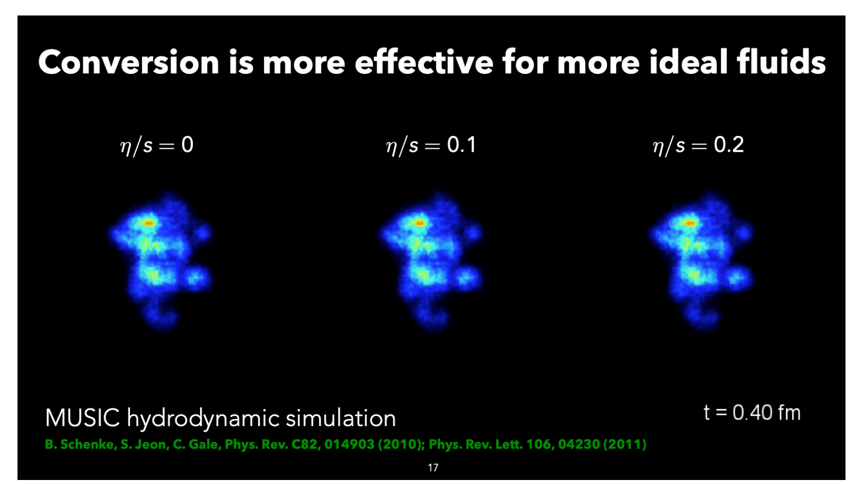
From initial anisotropy to anisotropic flow

J.Y. Ollitrault, PRD46 (1992) 229



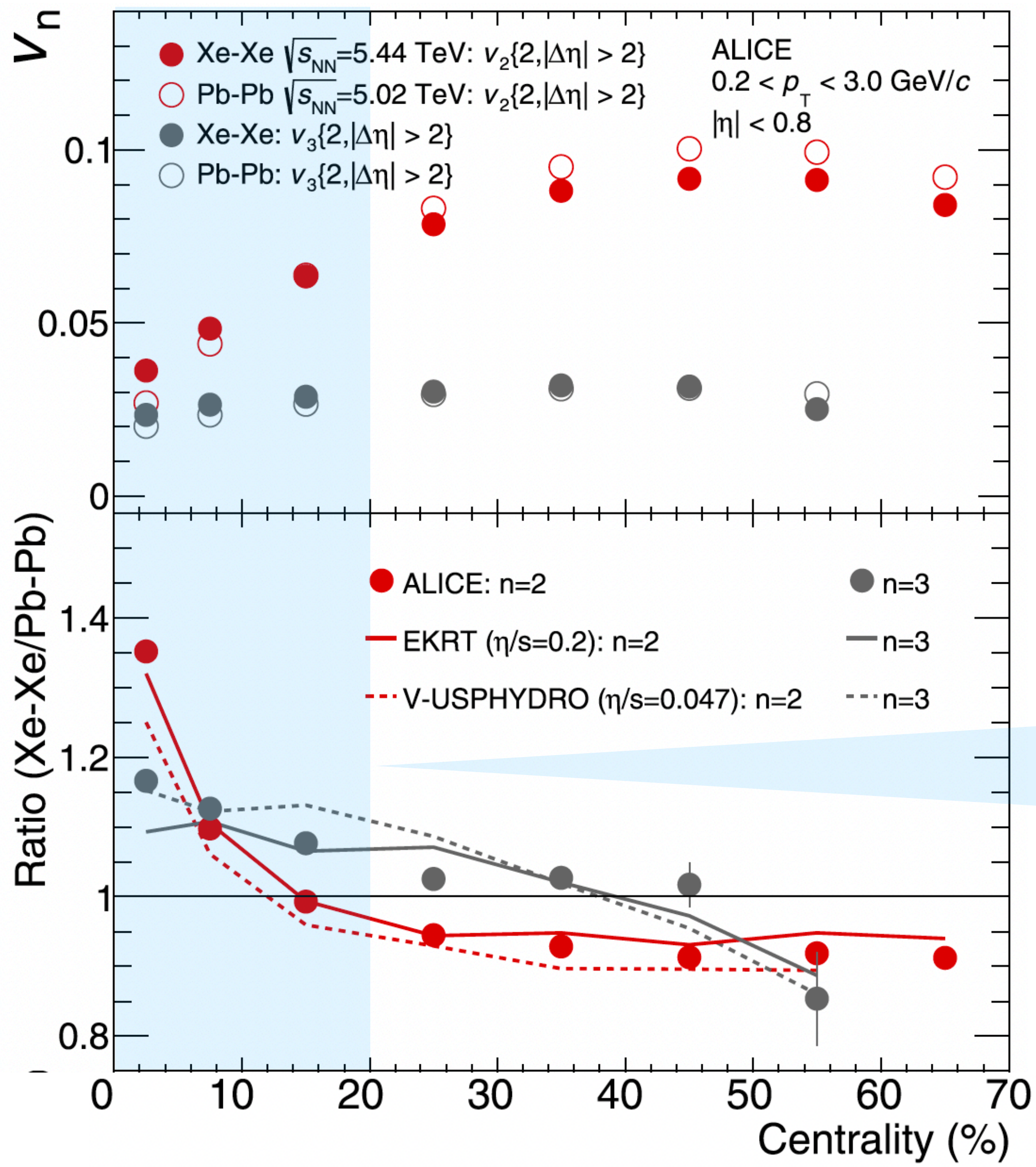
The whole idea works at the LHC where "perfect fluid" has been produced.

See Talk: B. Schenke

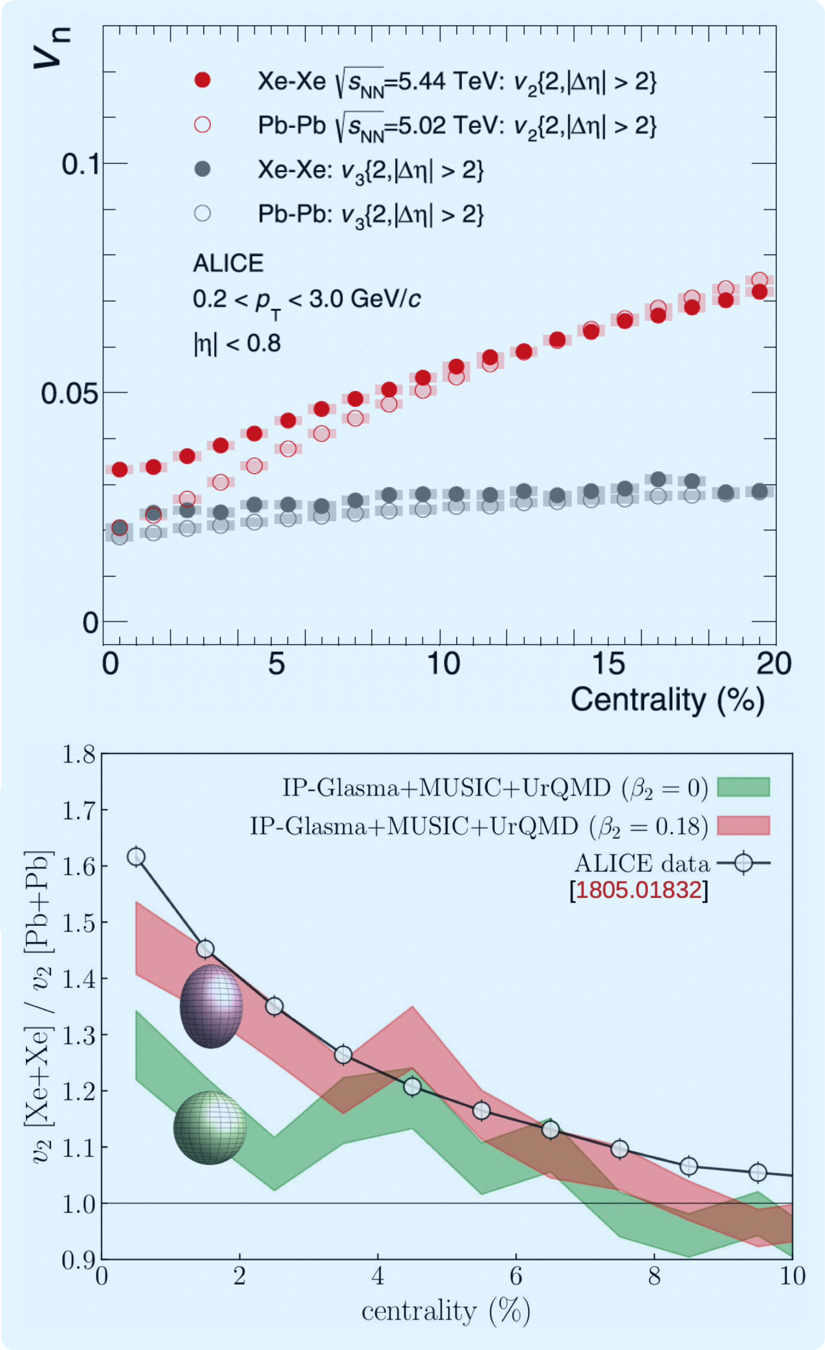


Probe deformation of ^{129}Xe at the LHC

ALICE, Physics Letters B 784 (2018) 82
EKRT: K.J. Eskola etc, PRC 97(3) (2018) 034911
v-USPhydro: G. Giacalone etc, PRC 97 (2018) 034904



Zoom-in



- Significant v_2 enhancement in central Xe-Xe collisions, originated from large deformation
- Reproduced by hydro model with $\beta_2 \sim 0.16$

P(v_m, v_n, v_k,…, Ψ_m, Ψ_n, $\Psi_{k,\ldots}$)

A reminder

J. Jia, JPG41 (2014) 124003

	pdfs	cumulants
Flow-amplitudes	$p(v_n)$	$v_n\{2k\}$, $k = 1,2,...$
	$p(v_n, v_m)$	$\langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle$, $n \neq m$ ...
	$p(v_n, v_m, v_l)$	$\langle v_n^2 v_m^2 v_l^2\rangle + 2\langle v_n^2\rangle\langle v_m^2\rangle\langle v_l^2\rangle -$ $\langle v_n^2 v_m^2\rangle\langle v_l^2\rangle - \langle v_m^2 v_l^2\rangle\langle v_n^2\rangle - \langle v_l^2 v_n^2\rangle\langle v_m^2\rangle$ $n \neq m \neq l$ ...
	...	Obtained recursively as above
EP-correlation	$p(\Phi_n, \Phi_m, ...)$	$\langle v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle$ $\sum_k kc_k = 0$
Mixed-correlation	$p(v_l, \Phi_n, \Phi_m, ...)$	$\langle v_l^2 v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle -$ $\langle v_l^2\rangle\langle v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle$ $\sum_k kc_k = 0$, $n \neq m \neq l ...$

PHYSICAL REVIEW C **103**, 024913 (2021)

Generic algorithm for multiparticle cumulants of azimuthal correlations in high energy nucleus collisions

Zuzana Moravcova, Kristjan Gulbrandsen,* and You Zhou†
Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark

- ❖ What is the full potential of P(v_m, v_n, v_k,…, Ψ_m, Ψ_n, $\Psi_{k,\ldots}$) that can be easily studied with generic algorithm?
- ❖ P(v_m, v_n, v_k,…, Ψ_m, Ψ_n, $\Psi_{k,\ldots}$) -> P(ε_m, ε_n, ε_k,…, φ_m, φ_n, $\varphi_{k,\ldots}$) -> initial "shape" of the colliding nuclei?
  - P(v_m, v_n, v_k,…, Ψ_m, Ψ_n, $\Psi_{k,\ldots}$) -> P(ε_m, ε_n, ε_k,…, φ_m, φ_n, $\varphi_{k,\ldots}$), information from the IC was not destroyed during dynamic evolution of the system
  - P(ε_m, ε_n, ε_k,…, φ_m, φ_n, $\varphi_{k,\ldots}$) -> initial "shape" of the colliding nuclei, information from the nuclear structure was not washed out by large event-by-event fluctuations

$\langle p_T \rangle$ - v_n correlations

❖Shape of the fireball: Anisotropic flow

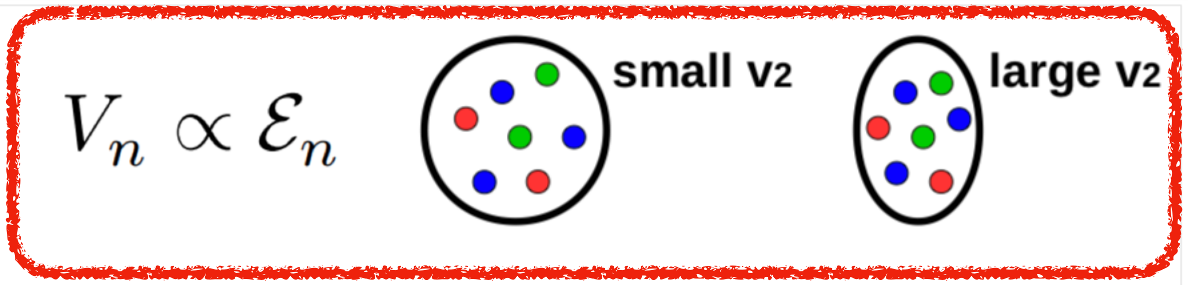
❖Size of the fireball: radial flow, $[p_T]$

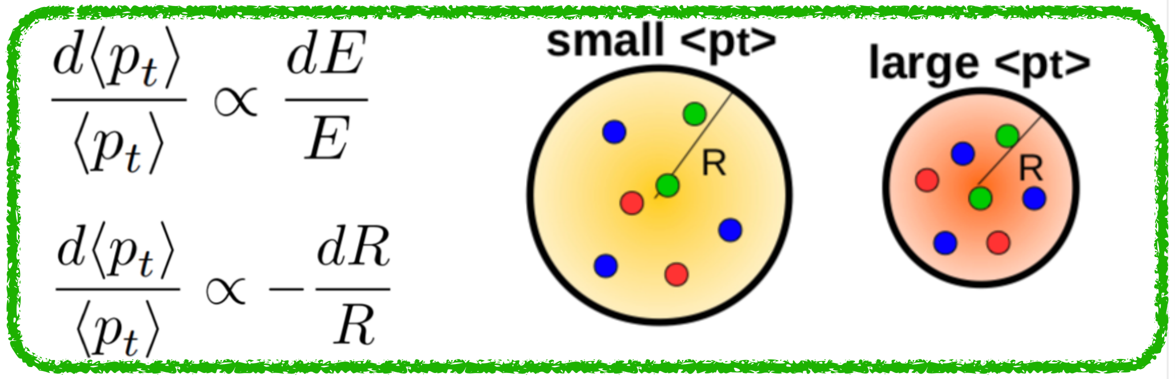
❖Initial geometry and fluctuations of shape and size

❖Final state: correlation between v_n and p_T

$$\rho(v_n^2, [p_T]) = \frac{cov(v_n^2, [p_T])}{\sqrt{var(v_n^2)}\sqrt{var([p_T])}}$$

P. Bozek etc, PRC96 (2017) 014904





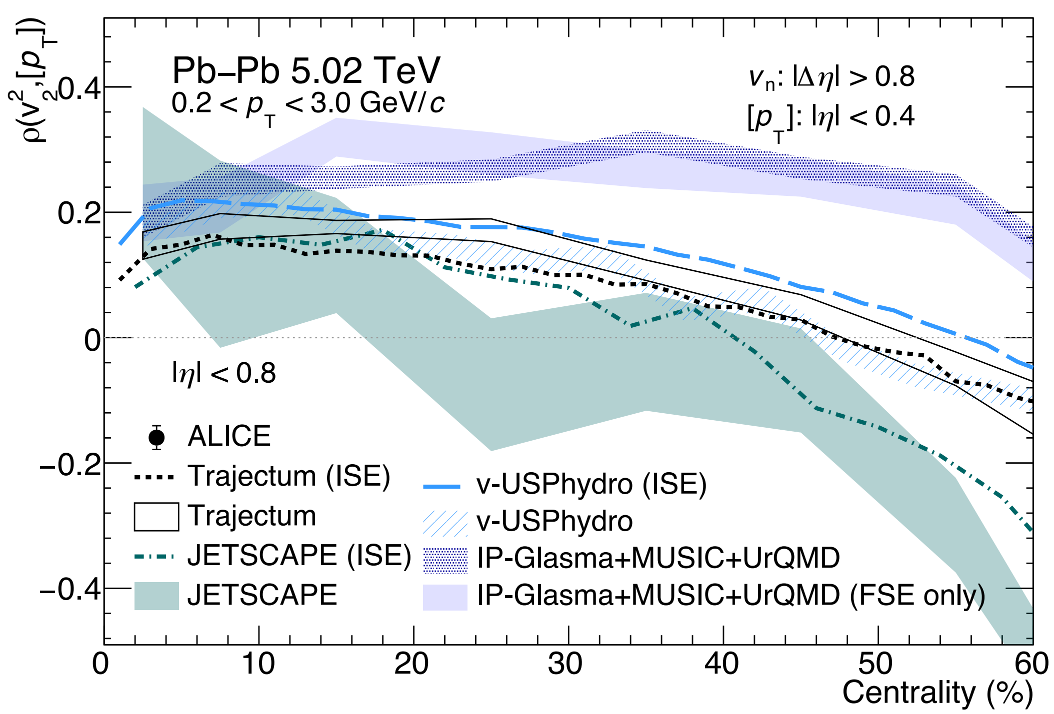
❖ Assuming $v_n \propto \varepsilon_n$, $[p_T] \propto E_0$

$$\rho(v_n^2, [p_T]) = \rho(\varepsilon_n^2, [E_0])$$

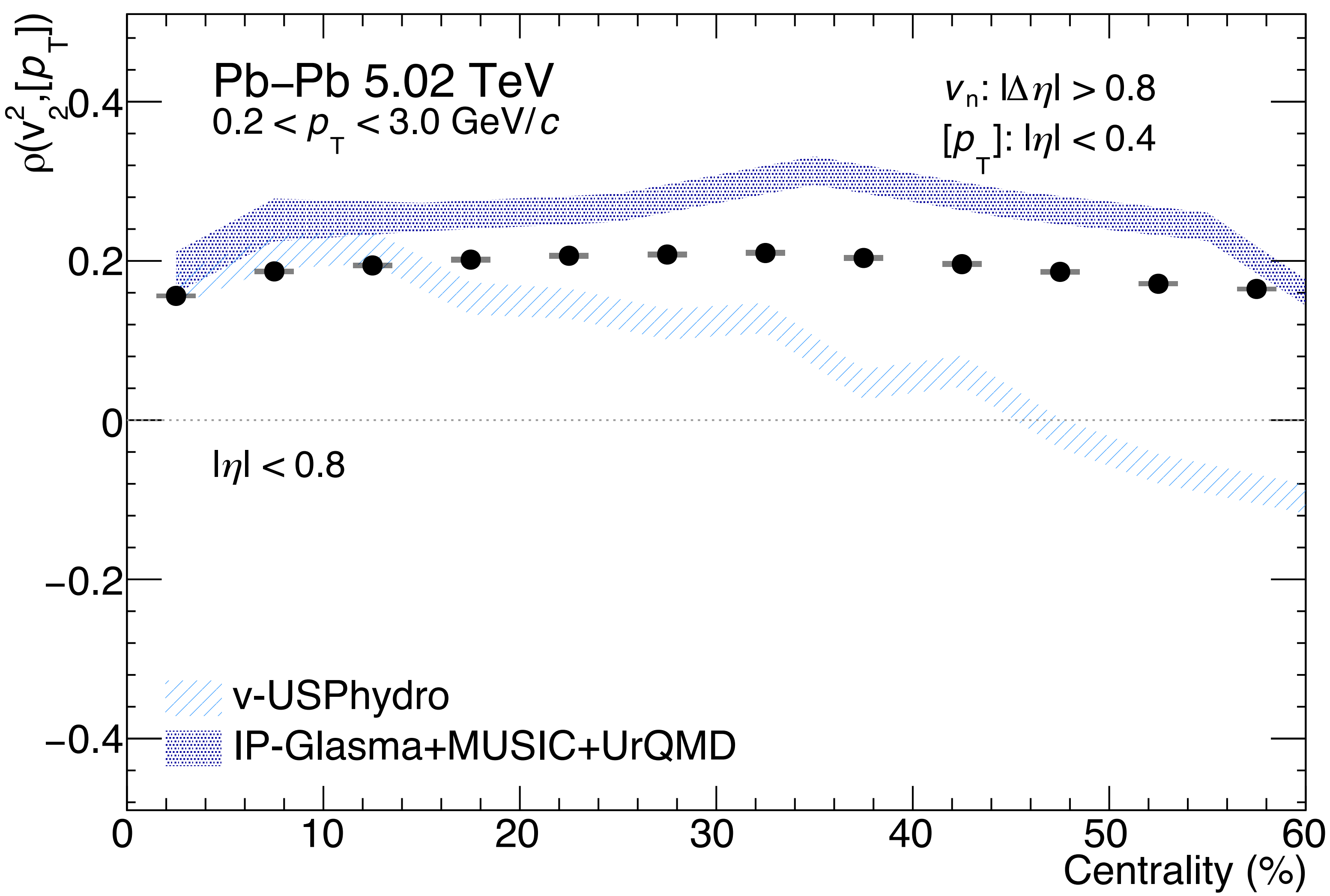
final-state model calculation

Initial-state model estimation

❖ One can compare $\rho(v_n^2, [p_T])$ measurements to $\rho(\varepsilon_n^2, [E_0])$ calculations, to constrain the initial state model



ρ_2 in Pb-Pb



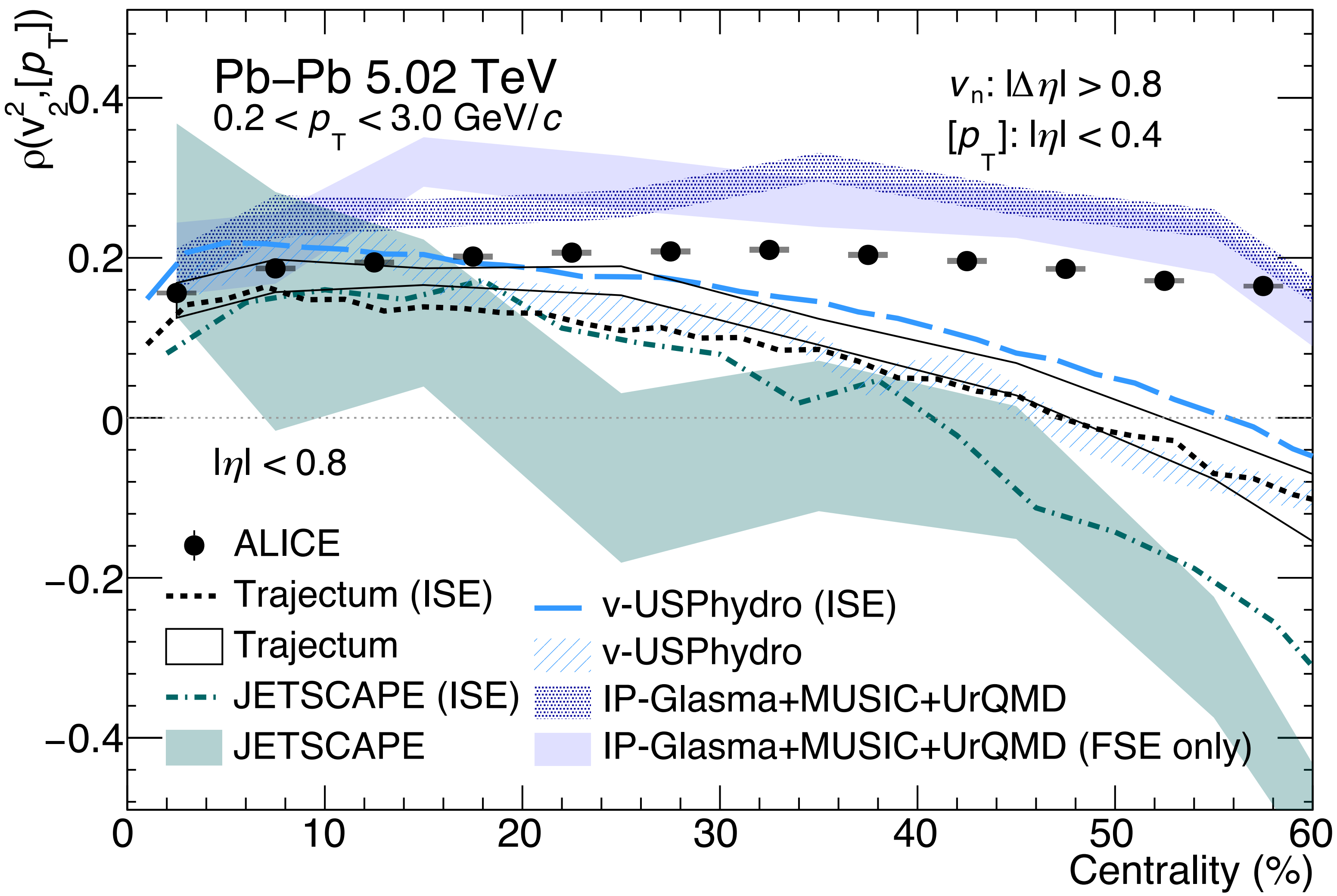
ALICE, arXiv: 2111.06106

v-USPhydro, PRC103 (2021) 2, 024909

IP-Glasma, PRC102, 034905 (2020)

- Weak centrality dependence of ρ_2 in Pb-Pb collisions,
  - IP-Glasma+MUSIC+UrQMD qualitatively describes the trend, overestimates the data
  - TRENTo-IC + v-USPhydro shows a very strong centrality dependence and wrong sign in peripheral
- Why there is such a huge difference between IP-Glasma+MUSIC+UrQMD and v-USPhydro ?

ρ_2 in Pb-Pb



ALICE, arXiv: 2111.06106

v-USPhydro, PRC103 (2021) 2, 024909

IP-Glasma, PRC102, 034905 (2020)

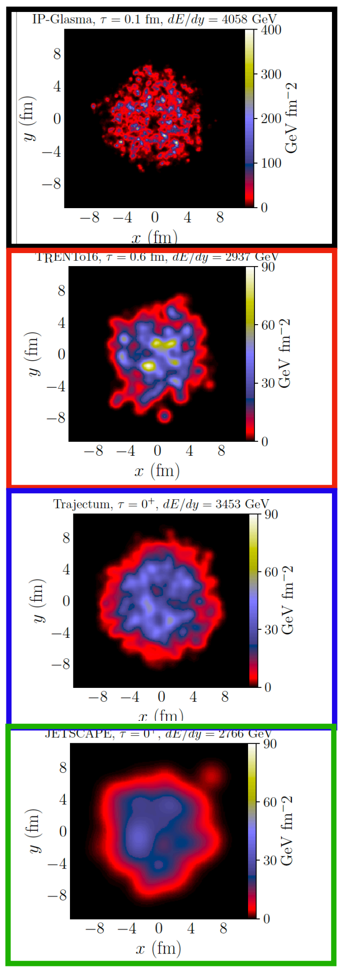
JETSCAPE, PRL126, 242301 (2021) Privation communication

Trajectum, PRL126, 202301 (2021) Privation communication

- TRENTo-IC based calculations all show strong centrality dependence, negative values for centrality >40%
  - v-USPhydro, Trajectum, JETSCAPE
- The difference is from the initial stage: geometric effects or initial momentum anisotropy (CGC)?
  - No significant difference between the "full IP-Glasma" and "FSE only" for the presented centralities
  - Difference not from initial momentum anisotropy and confirm the different geometric effects

Difference in IP-Glasma and TRENTo: potential explanations

- Sensitive to the nucleon width parameter (size of nucleon)
  - IP-Glasma ~ 0.4; v-USPhydro ~ 0.5; Trajectum~0.7; JETSCAPE (TRENTo) ~ 1.1
  - w(IP-Glasma) < w(v-USPhydro) < w(Trajectum) < w(JETSCAPE)
  - New constraints on the ***nucleon size***

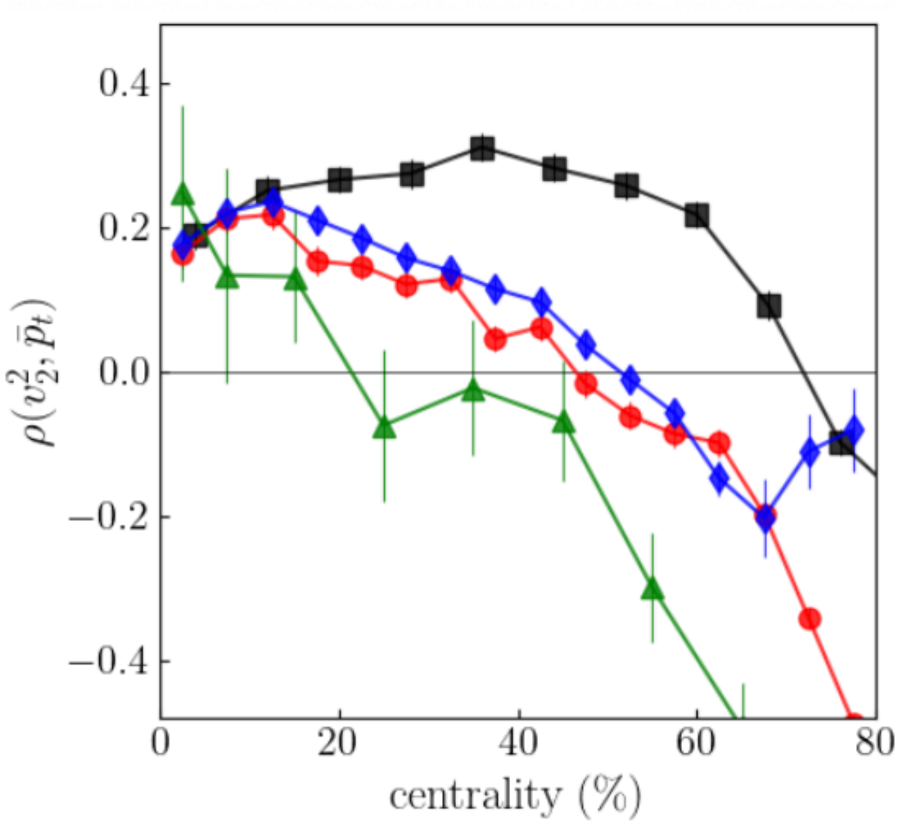


w ~ 0.4

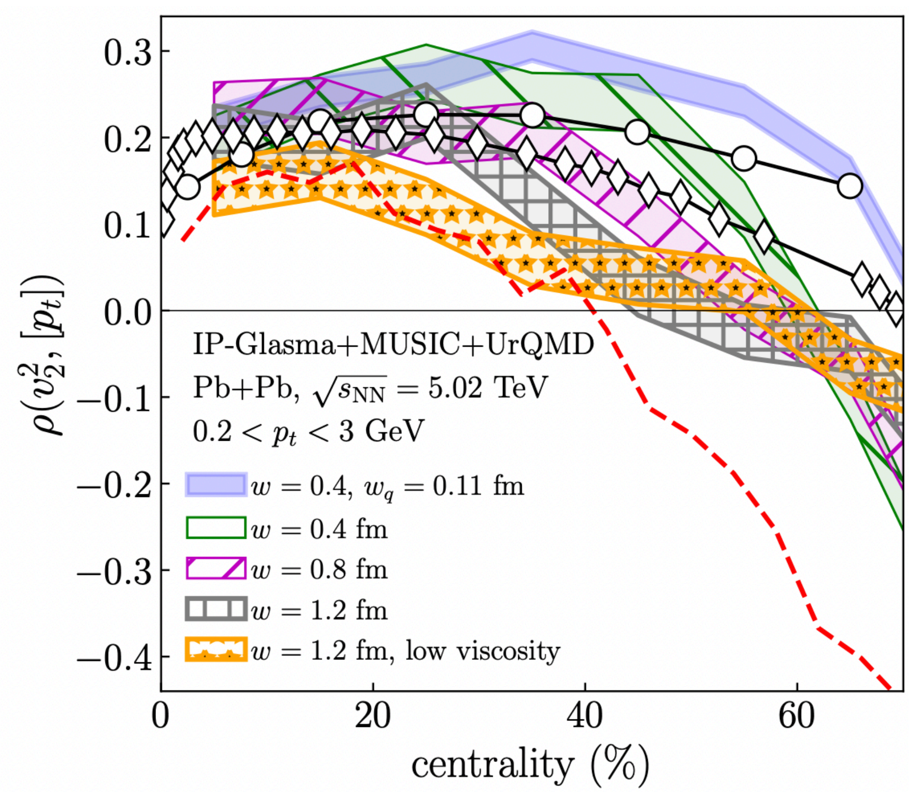
w ~ 0.5

w ~ 0.7

w ~ 1.1



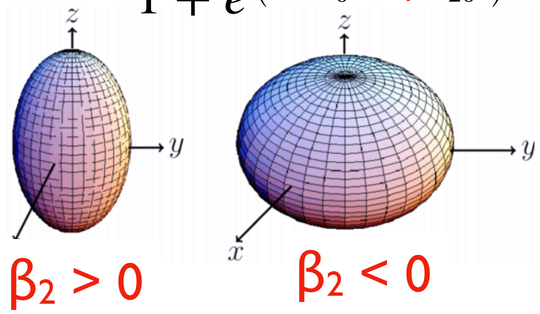
Giacalone, Schenke, Shen, arXiv: 2111.02908



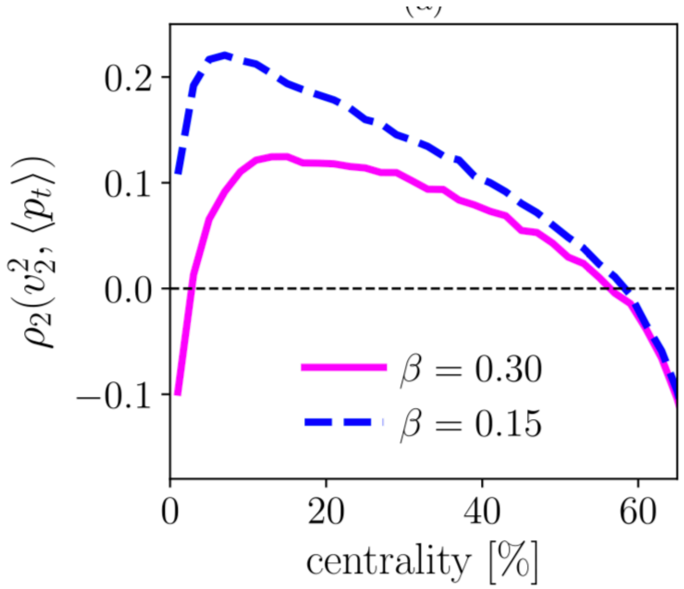
- Different types of thickness functions
  - TRENTo $\left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$ with p≈0 $\sqrt{T_A T_B}$, IP-Glasma $T_A T_B$ type
- Different contributions from pre-hydrodynamic phase (free streaming) and sub-nucleon structure

ρ_2 in Xe-Xe

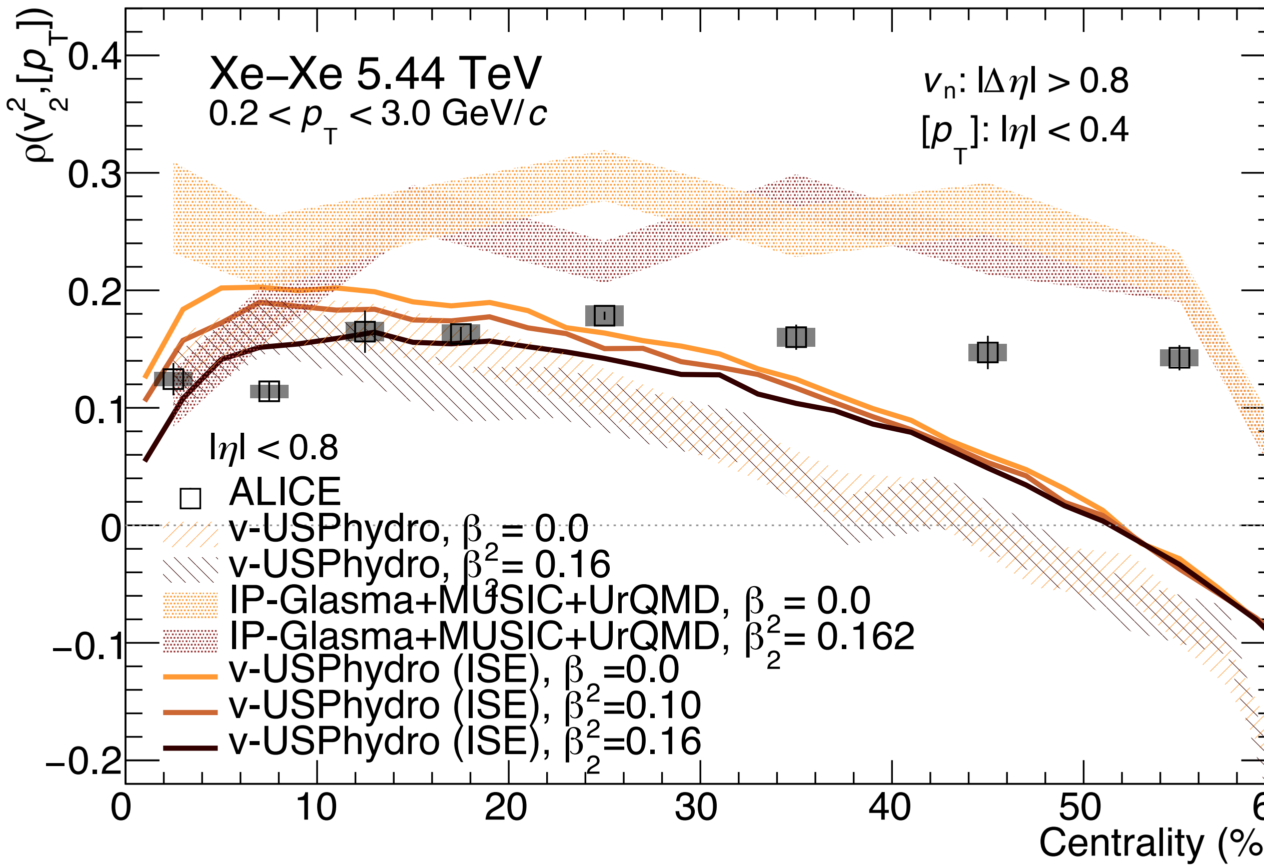
$$D_{WS} = \frac{D_0}{1 + e^{(r - R_0(1+\beta Y_{20}))/a}}$$



Pb—Pb: $\beta \approx 0$
Xe—Xe: $\beta \approx 0.16$



G.Giacalone, PRC 102 024901 (2020)



ALICE, arXiv: 2111.06106

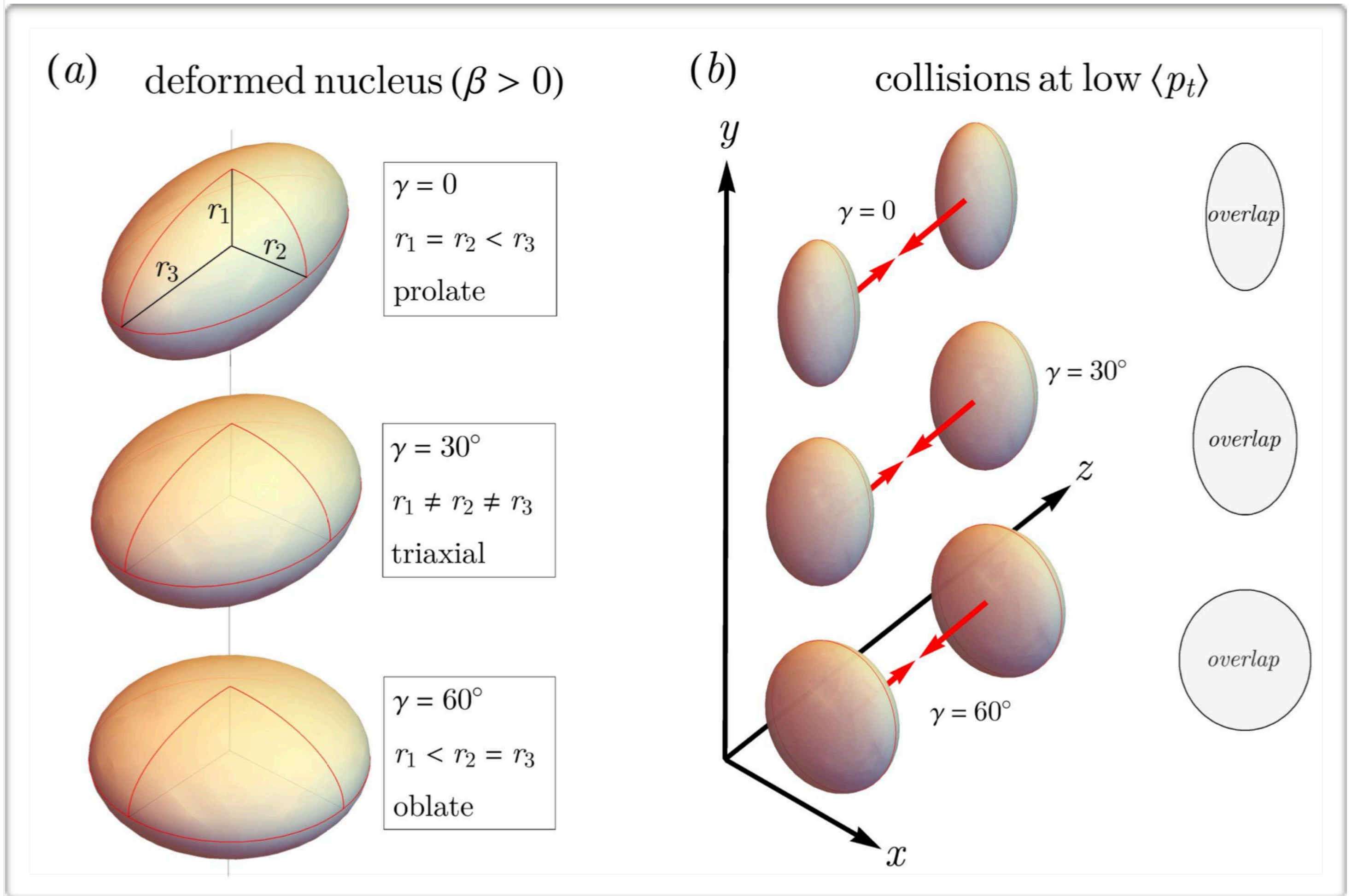
v-USPhydro, PRC103 (2021), 024909

IP-Glasma, PRC102, 034905 (2020)

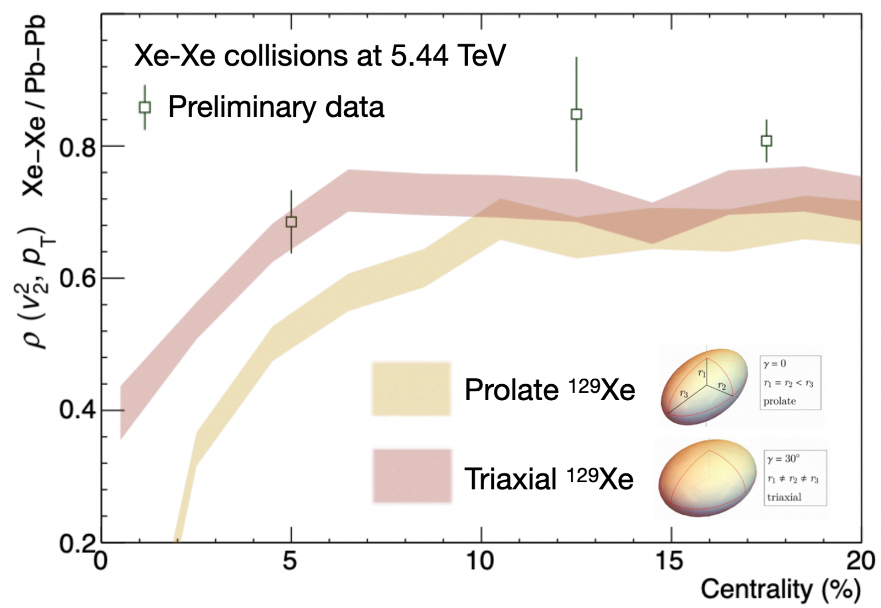
- ❖ Significant differences of initial state calculations using different deformation parameter in central Xe-Xe collisions
  - ρ_2 is sensitivties to β_2
  - The uncertainty of current v-USPhydro calculations is too large to draw a confirm conclusions
  - Experimental data (in Xe-Xe@LHC and U-U@RHIC) open a new window to study nucleon deformation.

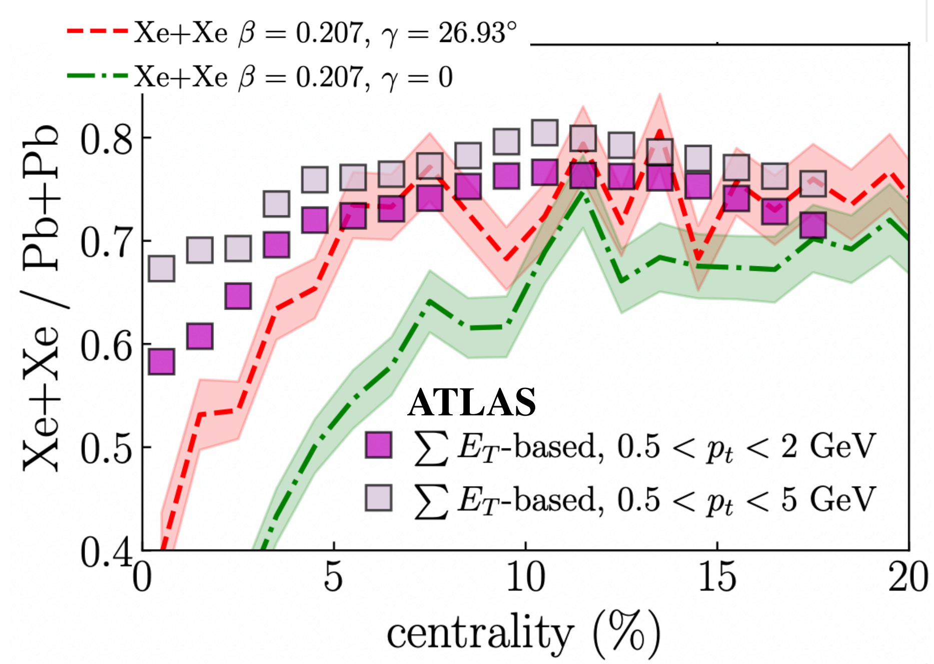
Probe triaxial structure of Xe

B. Bally etc, arXiv:2108.09578



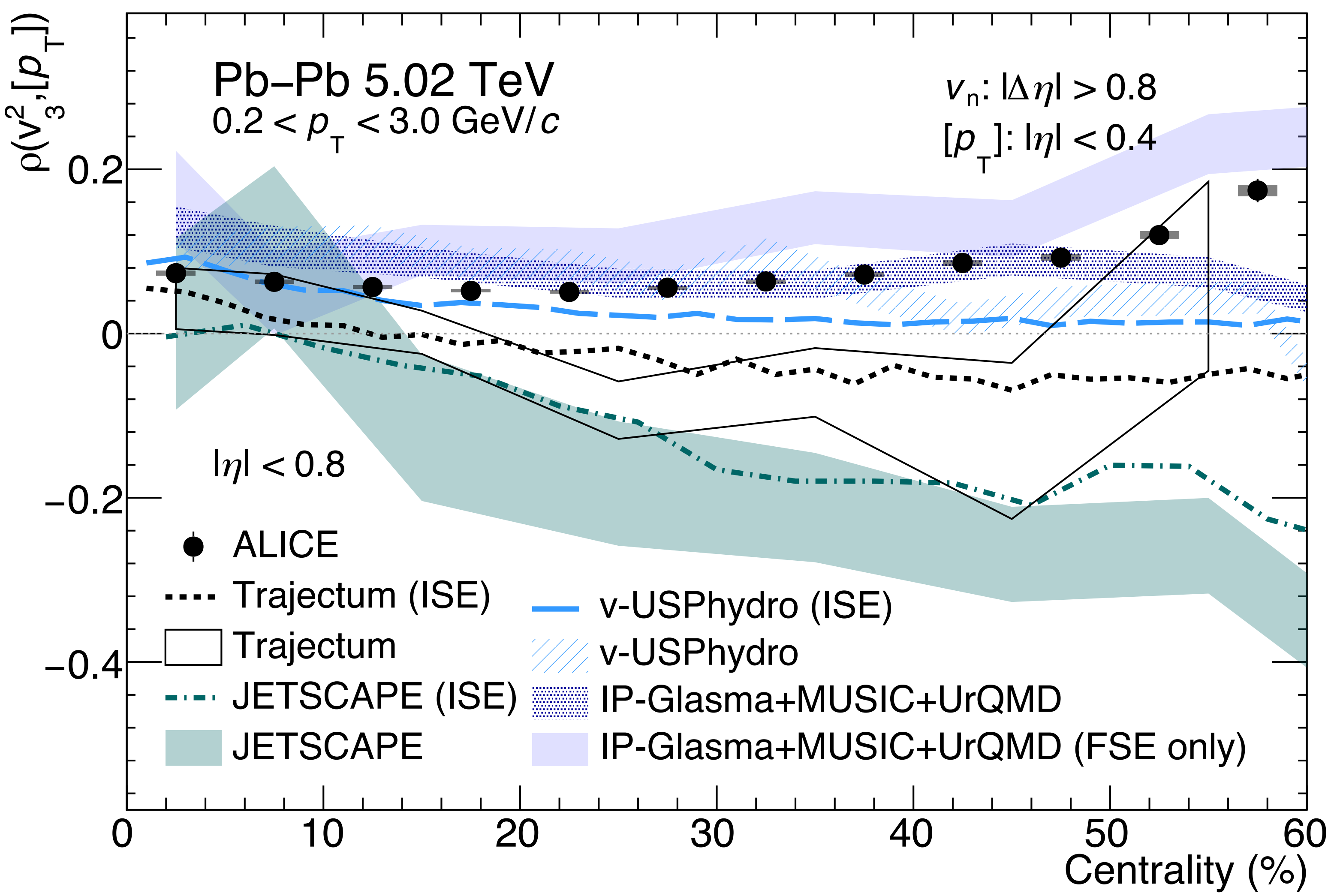
ALICE, arXiv: 2111.06106





- Better agreement between LHC data and calculations with $\gamma = 26.93°$
  - Indication of triaxial structure of ^{129}Xe at high energy collisions at the LHC
  - New connection of high-energy heavy-ion physics to low-energy nuclear (structure) physics

ρ_3 in Pb-Pb



ALICE, arXiv: 2111.06106

v-USPhydro, PRC103 (2021) 2, 024909

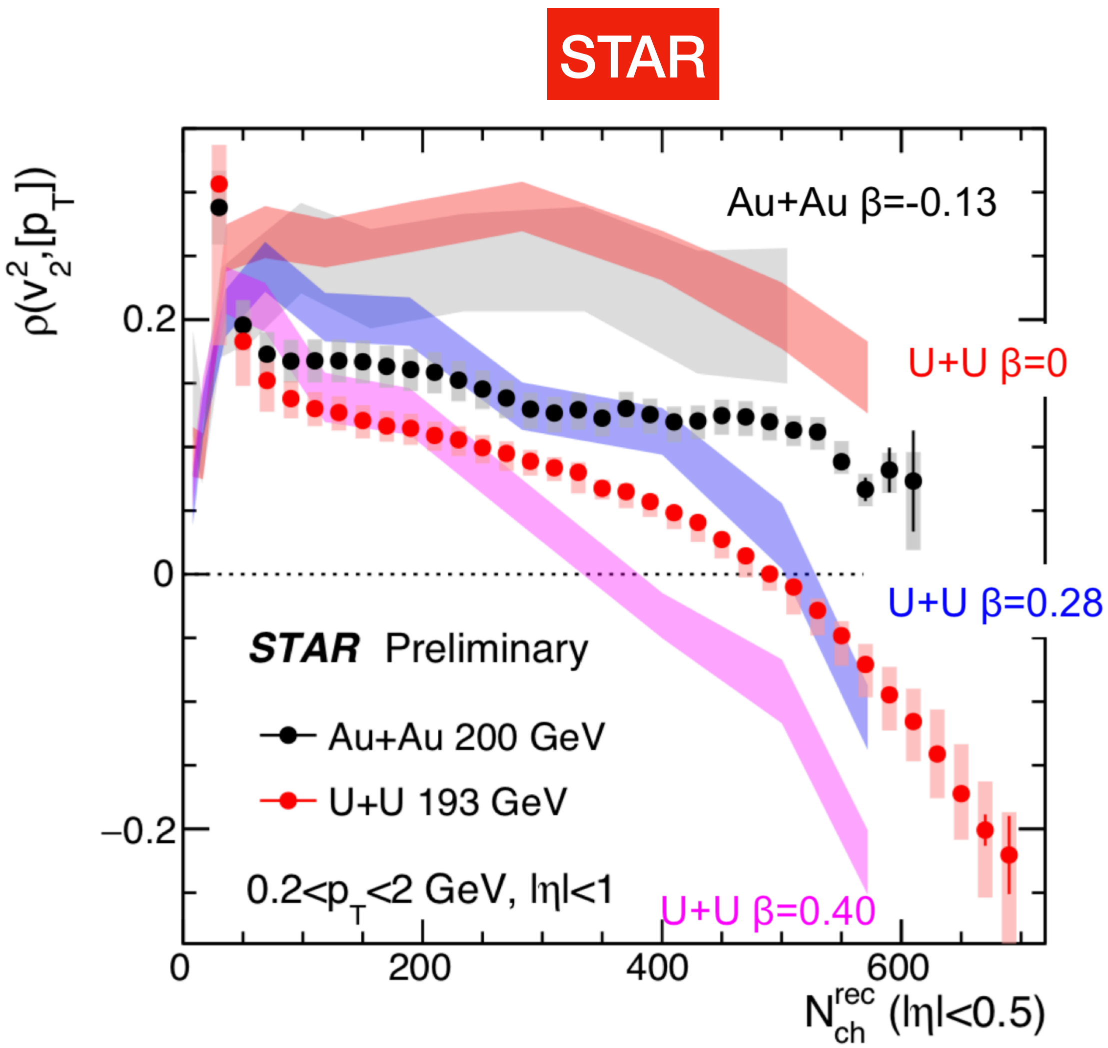
IP-Glasma, PRC102, 034905 (2020)

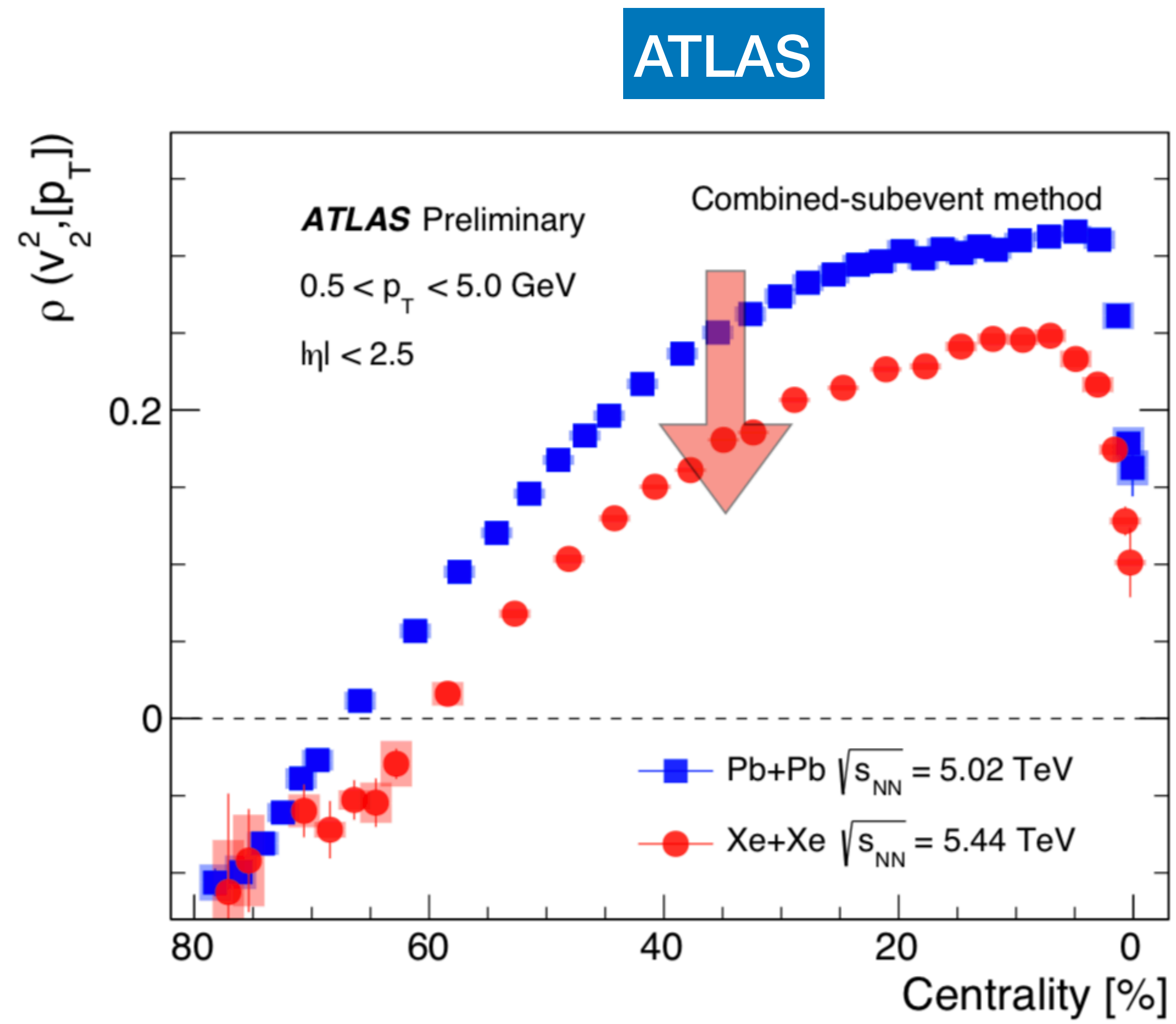
JETSCAPE, PRL126, 242301 (2021) Privation communication

Trajectum, PRL126, 202301 (2021) Privation communication

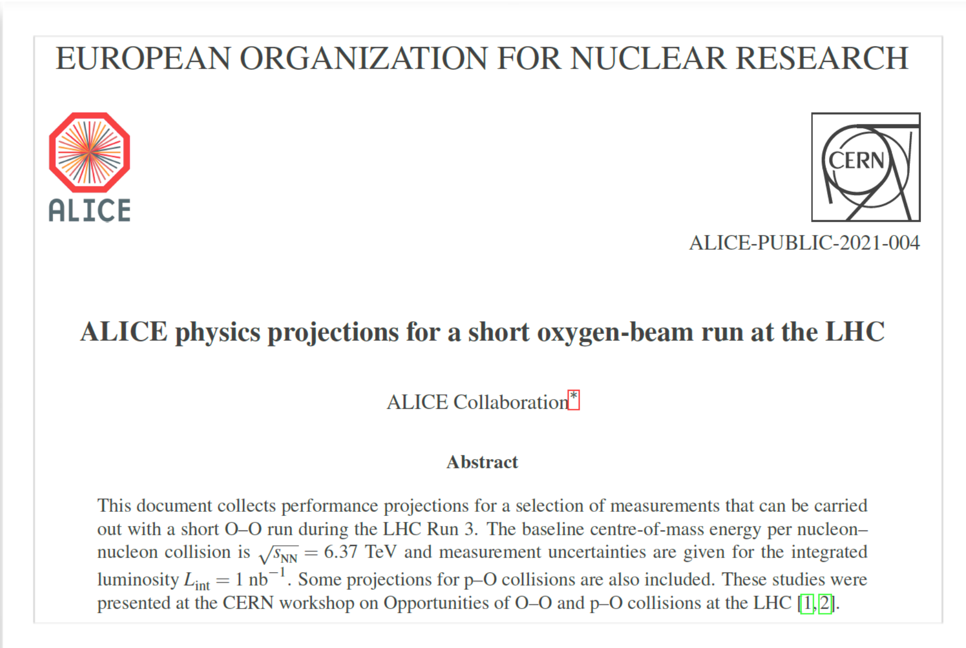
- ❖ ρ_3 values:
  - positive
  - have a modest centrality dependence for the presented centralities,
  - better described by IP-Glasma,
  - TRENTo predicts negative ρ_3, getting worse for Trajectum and JETSCAPE calculations
- ❖ model shows that ρ_3 is not sensitive to β_2
- ❖ Difference of full IP-Glasma and FSE only, indication of potential contributions from IMA in peripheral?

Many experimental efforts





O-O projection studies


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

CERN

ALICE-PUBLIC-2021-004

ALICE physics projections for a short oxygen-beam run at the LHC

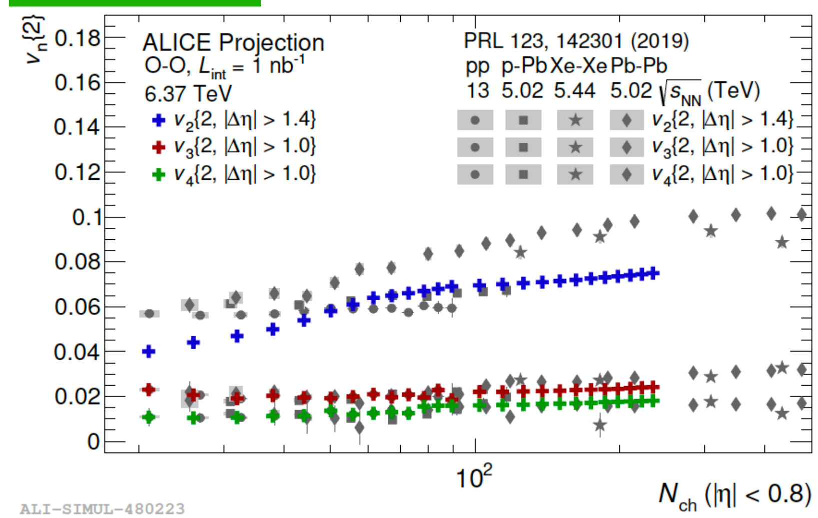
ALICE Collaboration[*]

Abstract

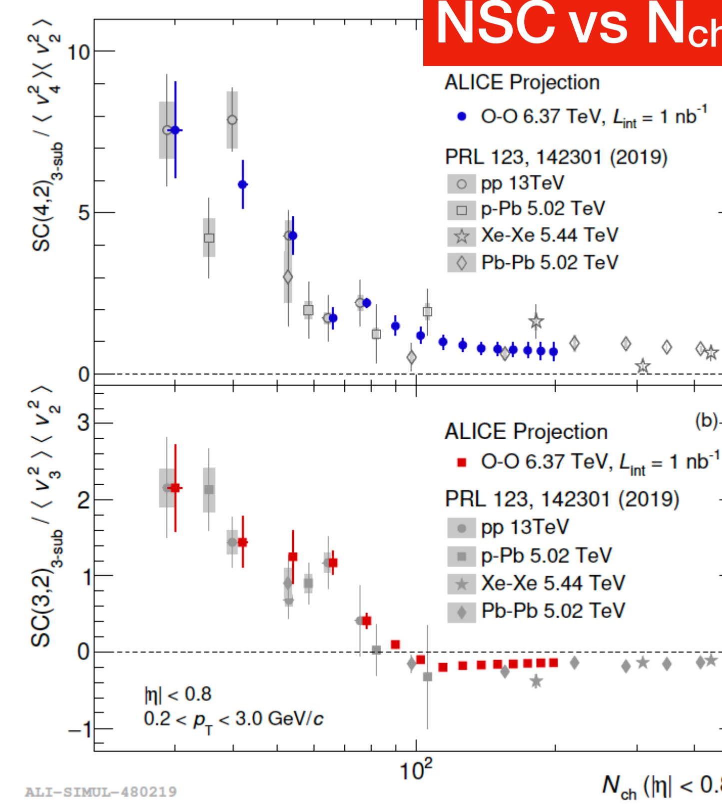
This document collects performance projections for a selection of measurements that can be carried out with a short O–O run during the LHC Run 3. The baseline centre-of-mass energy per nucleon–nucleon collision is $\sqrt{s_{NN}} = 6.37$ TeV and measurement uncertainties are given for the integrated luminosity $L_{int} = 1\ nb^{-1}$. Some projections for p–O collisions are also included. These studies were presented at the CERN workshop on Opportunities of O–O and p–O collisions at the LHC [1, 2].

(did not consider the structure of ^{16}O)

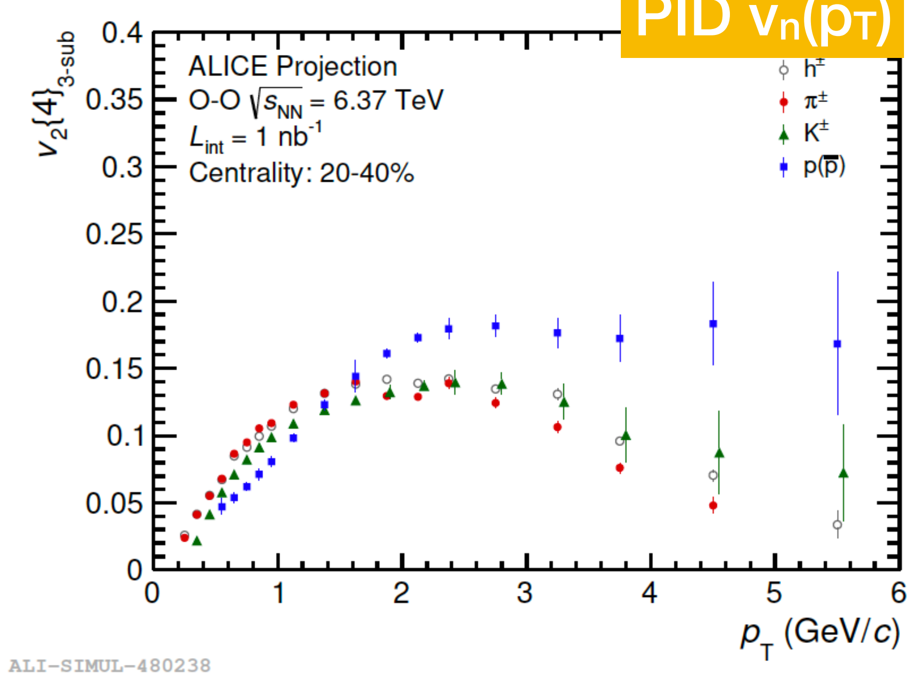
v_n vs N_{ch}



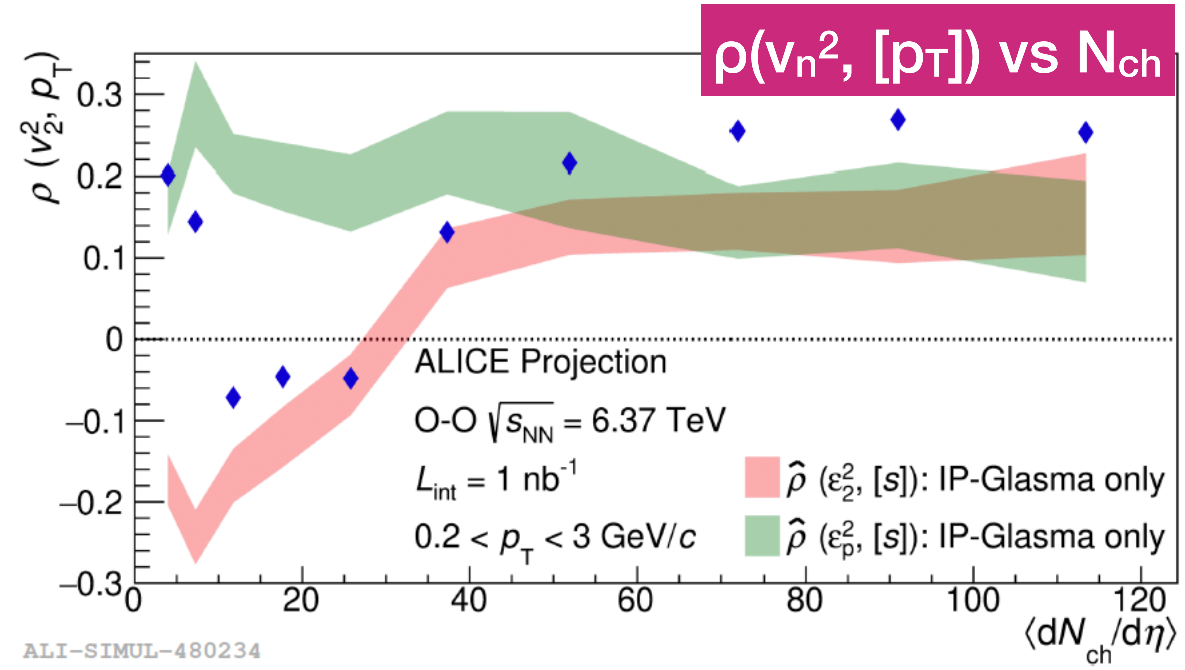
NSC vs N_{ch}



PID $v_n(p_T)$



$\rho(v_n^2, [p_T])$ vs N_{ch}



More discussions on O-O collisions, see Talk by D. Lee

Potential isobar runs at the LHC ?

CERN

CERN-LPCC-2018-07
February 26, 2019

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

Table 5: Parameters and performance for a range of light nuclei with an optimistic value of the scaling parameter $p = 1.9$ in (5).

	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
γ	3760.	3390.	3760.	3470.	3150.	2960.
$\sqrt{s_{NN}}$/TeV	7.	6.3	7.	6.46	5.86	5.52
σ_{had}/b	1.41	2.6	2.6	4.06	5.67	7.8
σ_{BFPP}/b	2.36×10^{-5}	0.00688	0.0144	0.88	15.	280.
σ_{EMD}/b	0.0738	1.24	1.57	12.2	51.8	220.
σ_{tot}/b	1.48	3.85	4.18	17.1	72.5	508.
N_b	1.58×10^{10}	3.39×10^{9}	2.77×10^{9}	9.08×10^{8}	4.2×10^{8}	1.9×10^{8}
ϵ_{xn}/μm	2.	1.8	2.	1.85	1.67	1.58
f_{IBS}/(m Hz)	0.168	0.164	0.184	0.18	0.17	0.167
W_b/MJ	175.	84.3	76.6	45.2	31.4	21.5
$L_{AA0}/\mathrm{cm}^{-2}s^{-1}$	9.43×10^{31}	4.33×10^{30}	2.9×10^{30}	3.11×10^{29}	6.66×10^{28}	1.36×10^{28}
$L_{NN0}/\mathrm{cm}^{-2}s^{-1}$	2.41×10^{34}	6.93×10^{33}	4.64×10^{33}	1.89×10^{33}	1.11×10^{33}	5.88×10^{32}
P_{BFPP}/W	0.0199	0.601	0.935	11.	60.6	350.
P_{EMD1}/W	32.	55.6	52.2	78.3	107.	141.
τ_{L0}/h	6.45	11.6	13.1	9.74	4.96	1.57
T_{opt}/h	5.68	7.62	8.08	6.98	4.98	2.8
$\langle L_{AA} \rangle\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	4.54×10^{31}	2.45×10^{30}	1.69×10^{30}	1.68×10^{29}	2.95×10^{28}	3.8×10^{27}
$\langle L_{NN} \rangle\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.16×10^{34}	3.93×10^{33}	2.71×10^{33}	1.02×10^{33}	4.91×10^{32}	1.64×10^{32}
$\int_{month} L_{AA}\ \mathrm{dt/nb}^{-1}$	5.89×10^{4}	3180.	2190.	218.	38.2	4.92
$\int_{month} L_{NN}\ \mathrm{dt/pb}^{-1}$	1.51×10^{4}	5090.	3510.	1330.	636.	213.
R_{had}/kHz	1.33×10^{5}	1.12×10^{4}	7540.	1260.	378.	106.
μ	10.6	0.893	0.598	0.1	0.03	0.00842

Summary

The recent LHC measurements on anisotropic flow v_n and correlations between v_n and $[p_T]$ have been presented.

☆ **Initial geometry:**

- Direct and indirect constraints on the initial state models
- For the first time we see completely different flow behaviours using IP-Glasma and TRENTo initial state models, due to the different geometric effects

☆ **Initial momentum anisotropy:**

- The observed differences from different models are not originated from initial momentum anisotropy (IMA)

☆ **Nuclear structure**

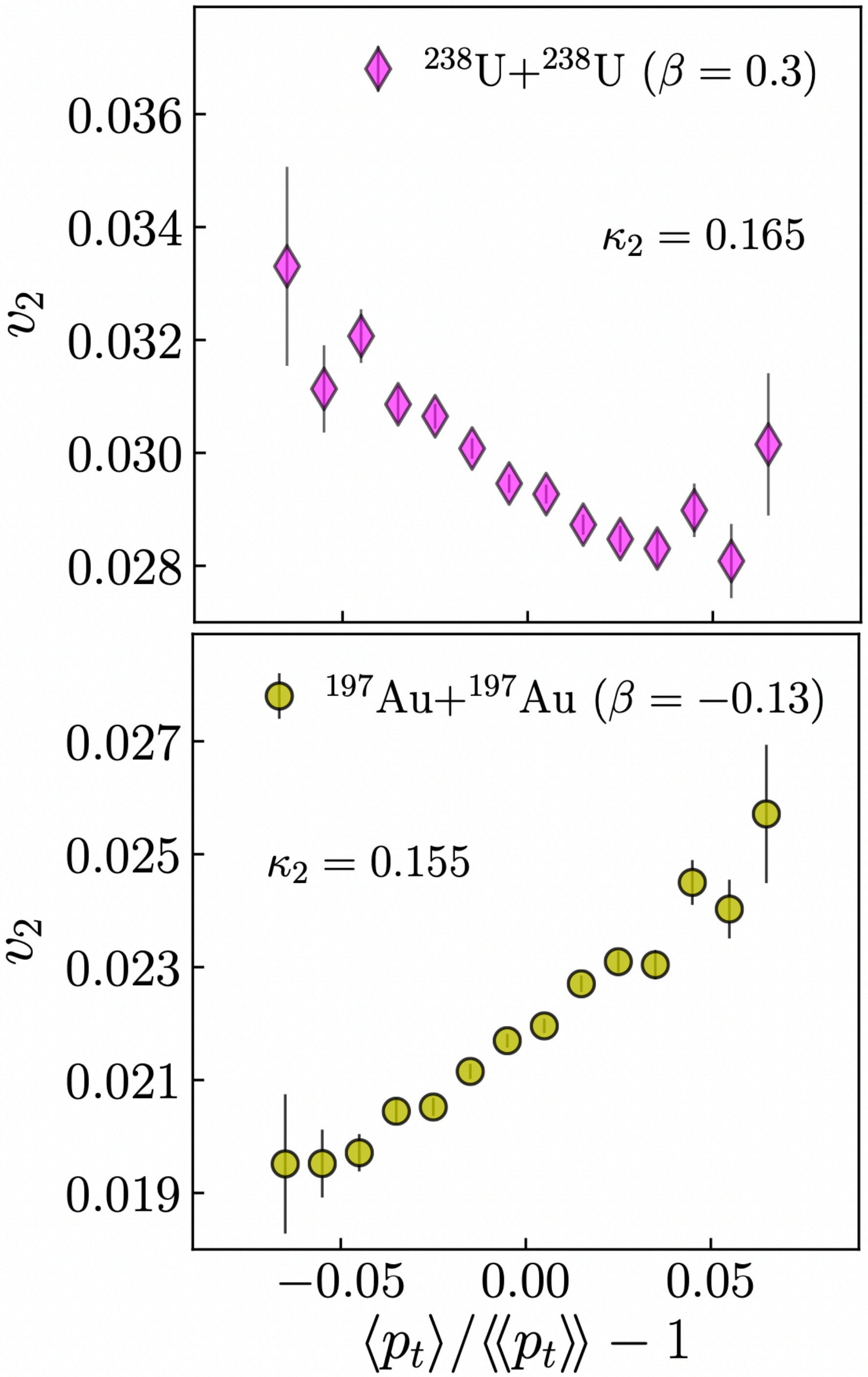
- New LHC data open a new window to explore the triaxial structure of nuclei (^{129}Xe, ^{16}O etc).
- Extremely important to check if the structure at high energy (at RHIC and the LHC) can be characterised by the same set of parameters (where the relevant degree of freedom might not be the same).
- Time to think about the impact of potential isobar runs at the LHC.

Thanks for your attention!

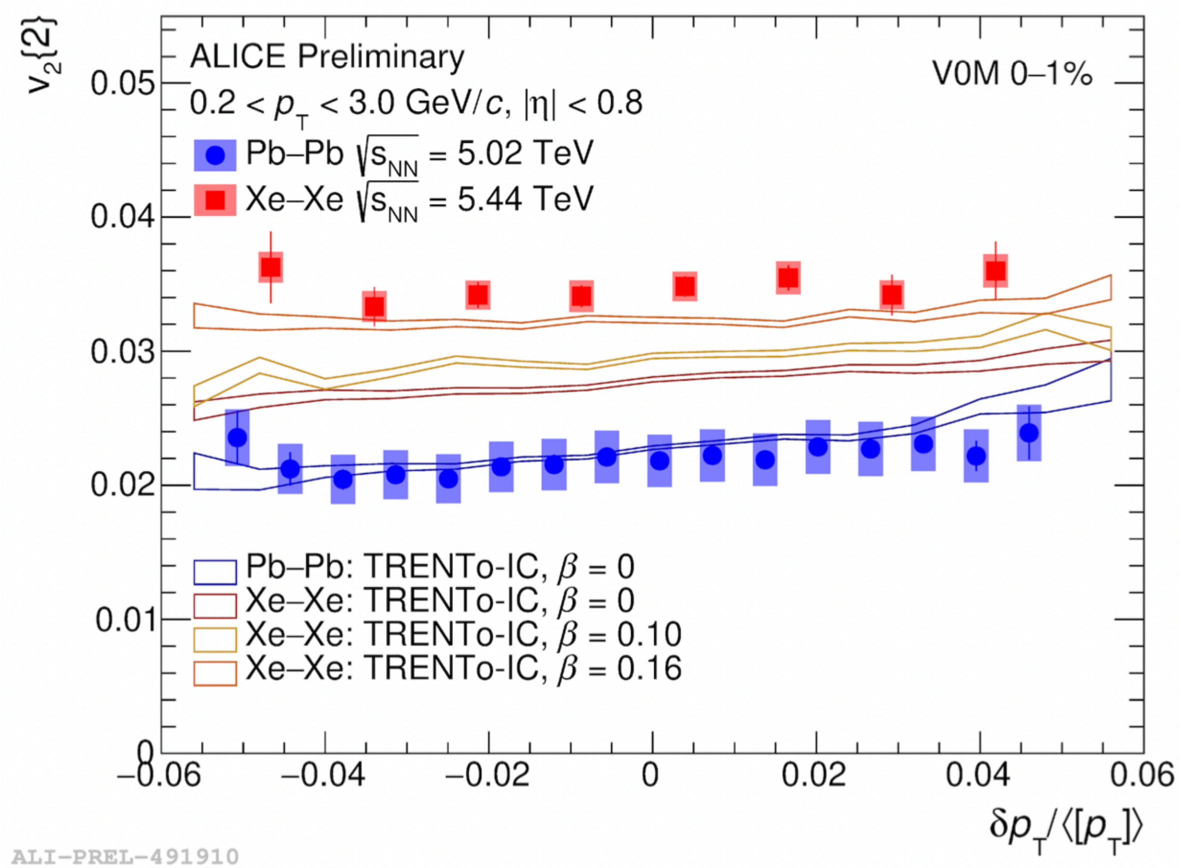
Backup

Probe deformation of ^{129}Xe at the LHC

G. Giacalone, PRC 102, 024901 (2020)



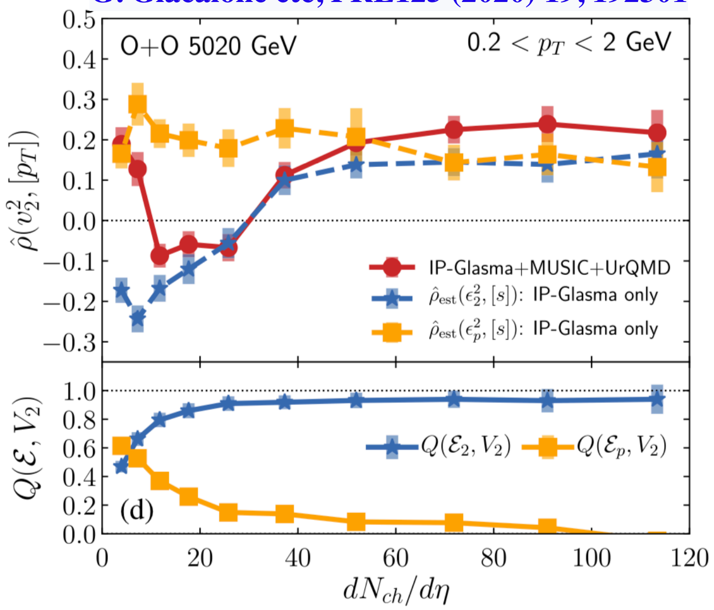
E.G. Nielsen @EPS-HEP2021



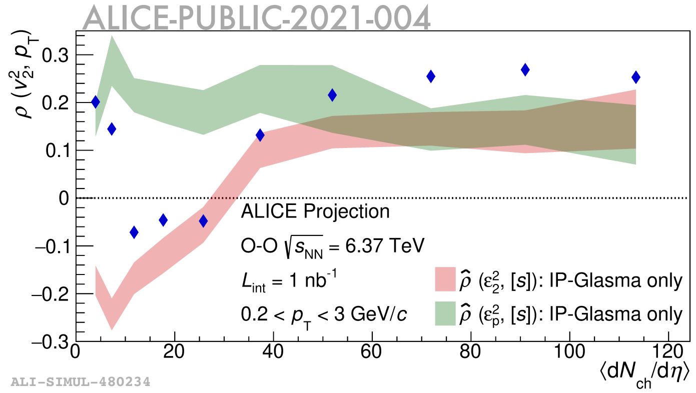
- Further zoom-in into 0-1% ultra-central collision
  - Significant v_2 enhancement
  - Weak dependence on δp_T
  - Data best described by $\beta_2 = 0.16$

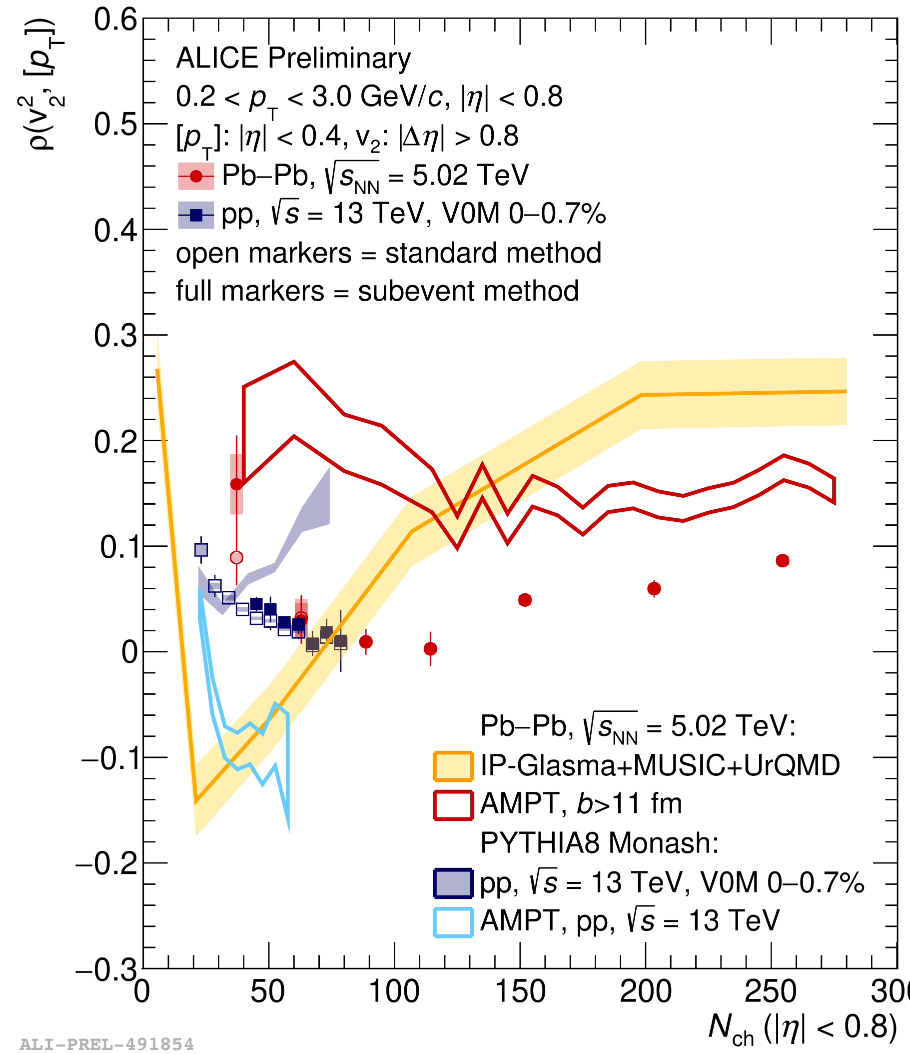
More results in smaller colliding systems

G. Giacalone etc, PRL125 (2020) 19, 192301



ALICE-PUBLIC-2021-004





- Search for the initial momentum anisotropy (IMA) in smaller colliding systems
  - Peripheral Pb-Pb collisions
    - Slope changes for N_{ch} ~ 100 for data and ~ 20 for IP-Glasma calculations
    - Both AMPT and IP-Glasma+hydro predicts slope changes -> not unique signature of IMA?
  - pp collisions:
    - Decreasing trend with increasing N_{ch}, results are consistent with the one in Pb-Pb
    - AMPT generates stronger anti-correlations, PYTHIA predicted a wrong N_{ch} dependence
    - Non-flow is a main challenge, many important studies by J. Jia, C. Zhang, J. Nagle etc

Higher-order correlations

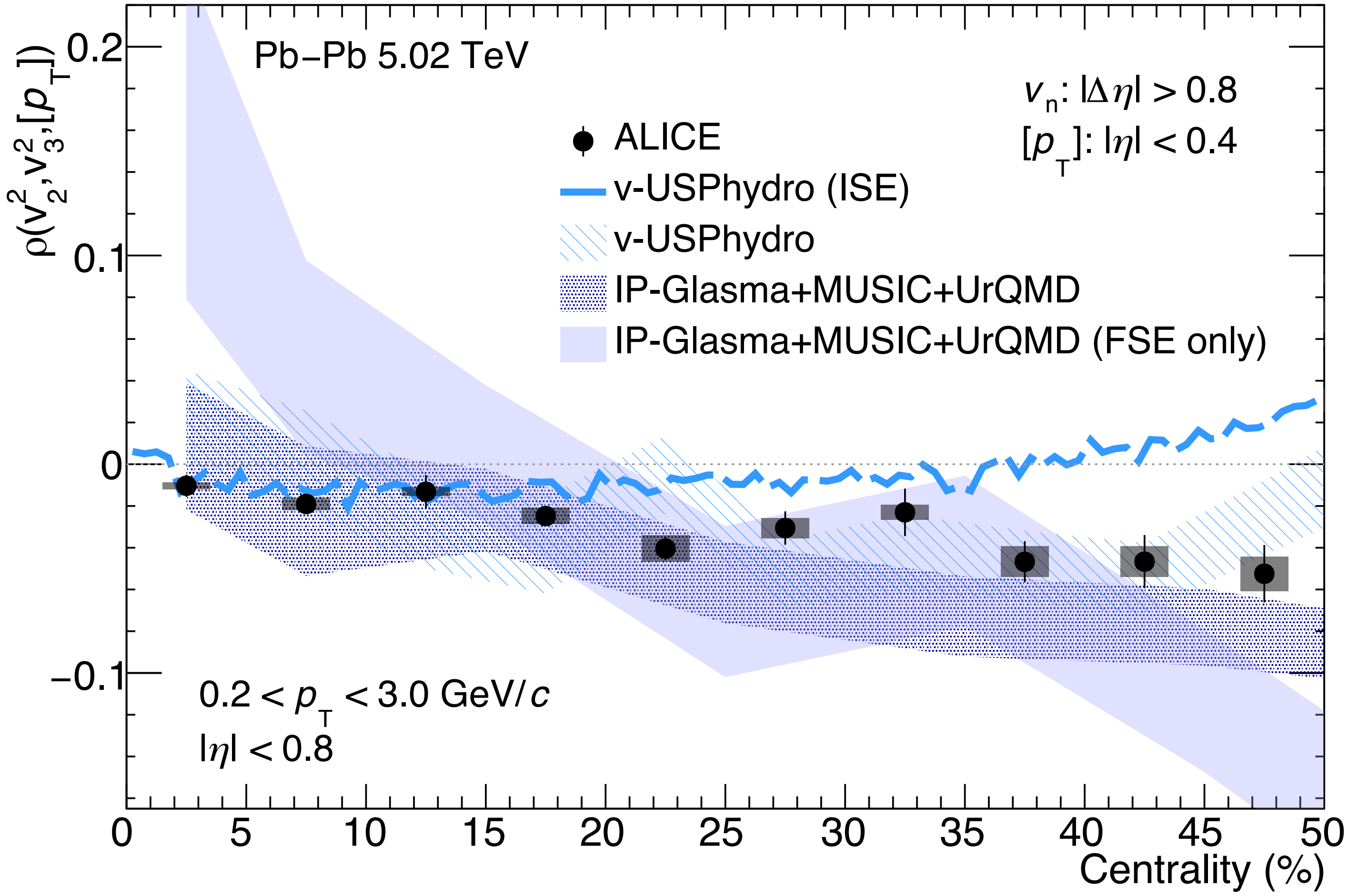
❖ The **first** measurement of higher-order [p_T], v_2 and v_3 correlations **P. Bozek etc, PRC104 (2021) 1, 014905**

$$\rho(v_m^2, v_n^2, [p_T]) = \frac{C(v_m^2, v_n^2, [p_T])}{\sqrt{\mathrm{Var}(v_m^2)}\sqrt{\mathrm{Var}(v_n^2)}\sqrt{c_k}} - \frac{\langle v_m^2 \rangle}{\sqrt{\mathrm{Var}(v_m^2)}} \cdot \rho_n - \frac{\langle v_n^2 \rangle}{\sqrt{\mathrm{Var}(v_n^2)}} \cdot \rho_m - \frac{\langle [p_T] \rangle}{\sqrt{c_k}} \cdot \frac{SC(m,n)}{\sqrt{\mathrm{Var}(v_m^2)}\sqrt{\mathrm{Var}(v_n^2)}}$$

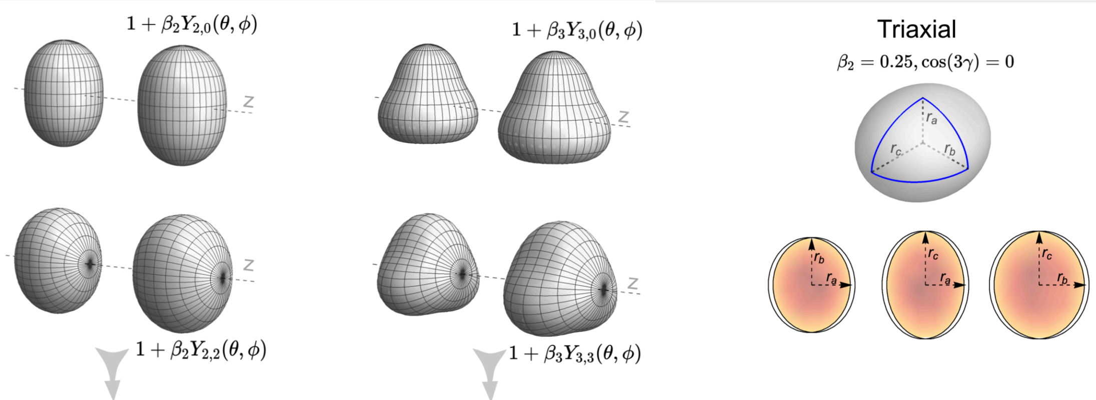
❖ the first ρ_{23} measurement is non-zero
- negative for the presented centrality
- anti-correlations between two flow coefficients and [p_T]

❖ ρ_{23} from IP-Glasma and v-USPhydro are different for centrality >40%
- Weaker centrality dependence of full IP-Glasma while strong dependence for FSE only, indication?
- More simulations are needed

❖ Not conclusive on which model works better due to sizeable uncertainties from model calculations



New connection to nuclear structure



Evidence of quadrupole and octupole deformations in ^{96}Zr+^{96}Zr and ^{96}Ru+^{96}Ru collisions at ultra-relativistic energies

Chunjian Zhang (SUNY, Stony Brook, Chem. Dept.), Jiangyong Jia (SUNY, Stony Brook, Chem. Dept. and Brookhaven)
Sep 3, 2021

6 pages
e-Print: 2109.01631 [nucl-th]

Probing triaxial deformation of atomic nuclei in high-energy heavy ion collisions

Jiangyong Jia (SUNY, Stony Brook, Chem. Dept. and Brookhaven)
Sep 1, 2021

23 pages
e-Print: 2109.00604 [nucl-th]

Shape of atomic nuclei in heavy ion collisions

Jiangyong Jia (SUNY, Stony Brook, Chem. Dept. and Brookhaven)
Jun 16, 2021

27 pages
e-Print: 2106.08768 [nucl-th]

Evidence of the triaxial structure of ^{129}Xe at the Large Hadron Collider

Benjamin Bally (Madrid, IFT), Michael Bender (IP2I, Lyon), Giuliano Giacalone (U. Heidelberg, ITP), Vittorio Somà (IRFU, Saclay)
Aug 21, 2021

8 pages
e-Print: 2108.09578 [nucl-th]

Constraining nuclear quadrupole deformation from correlation of elliptic flow and transverse momentum in nuclear collisions

Jiangyong Jia (SUNY, Stony Brook and Brookhaven), Shengli Huang (SUNY, Stony Brook), Chunjian Zhang (SUNY, Stony Brook)
May 12, 2021

13 pages
e-Print: 2105.05713 [nucl-th]

The impact of nuclear deformation on relativistic heavy-ion collisions: assessing consistency in nuclear physics across energy scales

Giuliano Giacalone (U. Heidelberg, ITP), Jiangyong Jia (SUNY, Stony Brook, Chem. Dept. and Brookhaven), Chunjian Zhang (SUNY, Stony Brook, Chem. Dept.)
May 4, 2021

6 pages
e-Print: 2105.01638 [nucl-th]

Accessing the shape of atomic nuclei with relativistic collisions of isobars

Giuliano Giacalone (Heidelberg U.), Jiangyong Jia (Stony Brook U. and Brookhaven), Vittorio Somà (IRFU, Saclay)
Feb 16, 2021

5 pages
Published in: *Phys.Rev.C* 104 (2021) 4, L041903
Published: Oct 20, 2021
e-Print: 2102.08158 [nucl-th]

❖ **Can we boost the LHC as a super machine for the nuclear structure study?**
- **with Pb-Pb, Xe-Xe, p-Pb, pp (Run2), p-O, O-O (Run3) and Ar-Ar ...(Run5)**